GEOPHYSICAL SURVEYS FOR ASSISTING IN DETERMINING THE GROUND WATER RESOURCES NEAR KAILUA, NORTH COAST ISLAND OF MAUI, HAWAII

Blackhawk Geometrics Project Number 9818A&B

Prepared For:
ALEXANDER AND BALDWIN PROPERTIES, INC.

BLACKHAWK
GEOMETRICS

Corporate Center
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RECEIVED
JUN 23 1998
TOM NANCE
WATER RESOURCE ENGINEERING

98209A&B
June 22, 1998

Ms. Meridith Ching
Alexander and Baldwin Properties, Inc.
822 Bishop Street
Honolulu, HI 96813

RE: Geophysical Surveys for Assisting in Determining the Ground Water Resources
Near Kailua, North Coast Island of Maui, Hawaii
Blackhawk Geometrics Project Number 9818A&B

Dear Meridith:

Enclosed are three (3) copies of our Final Report for the Kailua study site. A copy of this report is being forwarded to Tom Nance.

We appreciate this opportunity to work with you on this project. If you have any questions or comments, feel free to call Mark or myself.

Sincerely,
BLACKHAWK GEOMETRICS

Richard J. Blohm

Richard J. Blohm
Geologist

RB:lm

Enclosures

cc: Tom Nance

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Blackhawk Geometrics Project Number 9818A&B

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June 22, 1998

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1.0 INTRODUCTION

This report contains the results of geophysical surveys conducted to assist in determining the ground water resources in the vicinity of Kailua, Maui, Hawaii. The surveys were performed by Blackhawk Geometrics (Blackhawk) for Alexander and Baldwin Properties, Inc., (A&B) during May 8, 1998. The geophysical method employed during this survey was Time Domain Electromagnetic (TDEM) soundings. The TDEM soundings from this survey were located on property owned by A&B and are shown in Figure 1-1.

The main objective of the geophysical survey was to assist in characterizing the hydrologic regime in the study area for a proposed ground water well. Ground water resources mainly occur on the Island of Maui in two modes:

- In a basal mode where a lens of fresh water floats on saline water, and
- In a high-level mode where the ground water occurrence is controlled by subsurface damming structures.

These two types of ground water occurrences are illustrated in Figure 1-2. The volcanic rocks are generally highly permeable and this allows rainwater to infiltrate directly downward through the island mass. In the Kailua area, ground water was expected to occur mainly as a deep basal fresh/brackish water lens. High-level water resources were not expected at the study site.

From the results of the TDEM survey, a relatively thick basal fresh/brackish water resource is inferred. The lens of fresh/brackish water is expected to be about 200 ft thick under the area surveyed.

In the remaining part of this report, logistics and procedures of data acquisition and processing are explained, the principles of deriving hydrogeologic information are discussed, and the interpretation protocol is given.

2.0 DATA ACQUISITION AND LOGISTICS

The geophysical equipment used for the TDEM surveys was the Geonics EM37 TDEM System. TDEM measurements were acquired using a central-loop sounding array at each site. With this array, measurements are recorded with a receiver coil at the center of transmitter loops laid on the ground surface. The transmitter loops are constructed with 12-gauge insulated copper wire. The dimensions of the square loops employed at the Kailua study site were 500 ft by 500 ft and 700 ft by 700 ft. A 2.8 kW transmitter was placed in each sounding loop to drive current ranging from 14 to 19 amperes at base frequencies of 3 Hz and 30 Hz. At the center of each transmitter loop, the time derivative of the vertical magnetic field was recorded with a receiver coil with an effective area of 100 m^2. The data acquired at each sounding consisted of measurements at several receiver gain settings and two transmitter frequencies in order to assure data quality and to obtain data over the largest time interval possible. Data quality at each site was excellent. The data from each sounding was stored in the field on an Omnidata polycorder and, subsequently, transferred to a PC-486 for nightly processing. A technical note describing the principles of TDEM with case histories is given in Appendix A.

During the one and one-half days of field work, two soundings were completed at the Kailua survey site. A daily log of field activity is given in Table 2-1. The elevation of each sounding center was measured using an Avocet Vertech Altimeter/Barometer. The altimeter was adjusted at landmarks (i.e., roads) with known altitudes from a 7.5 minute series topographic map of the Kailua area. The loop locations were selected by representatives of A&B and Blackhawk. The sounding locations were based on property ownership, available land, and exploration objectives and they were measured by compass and hip-chain from known landmarks.

TABLE 2-1 DAILY LOG OF FIELD ACTIVITIES	
DATE, 1998	ACTIVITY
May 1	Mobilize geophysical equipment from Golden, CO, to Maui, HI
May 4	Mobilize Blackhawk Geometrics personnel from Golden, CO, to Maui, HI
May 5	Pick up geophysical equipment from airport & organize into field vehicles. Begin surveys on other Maui projects.
May 6 - 9	Take TDEM data on other Maui projects.
May 10	Meet with A&B representative to discuss project. Acquire data on Sounding 1, above Kailua.
May 11	Data on other Maui projects.
May 12	Acquire data on Sounding 2, near water tank, above Kailua.
May 13 - 14	Data on other Maui projects.
May 15	Demobilize geophysical equipment from Maui, HI, to Golden, CO.
May 23	Demobilize Blackhawk Geometrics personnel from Maui, HI, to Golden, CO.

3.0 DATA PROCESSING

The TDEM field data acquired at the Kailua study site were transferred from the Omnidata polycorder to a PC-486. The first step in processing the TDEM data is to average the electromotive forces (emfs) recorded at positive and negative receiver polarities. Next, the recordings made at different amplifier gains and frequencies were combined to give one transient decay curve with the program TEMIXXL (Interpex LTD). With this program, voltages measured with the 20 channels of the Geonics EM37 receiver are transformed into apparent resistivity versus time gate. The apparent resistivity curve is interpreted by inversion to a one dimensional (1-D) geoelectric section that matches the observed decay curve.

The inversion program requires an initial estimate of the geoelectric section, including the number of layers and the thicknesses and resistivities of each of the layers. The program then adjusts these parameters so that the model curve converges to best fit the curve formed by the field data. The inversion program does not change the number of layers within the model, but allows all other parameters to change freely, or they can optionally be fixed constant. To determine the influence and best fit of the number of layers on the solution, separate inversions with different numbers of layers are run. Normally, the model with the fewest number of layers which adequately fits the data is used.

An example of the output of the inversion program is shown on Figures 3-1 and 3-2 for Sounding AB-1. Figure 3-1 shows the measured data points (in terms of apparent resistivity) superimposed on a solid line. The solid line represents the computed forward model of the geoelectric section shown on the right. Tabulated inversion parameters and results consisting of measured field data, computed data for best match solution, and inversion errors are given on Figure 3-2. The apparent resistivity curves and data sheets for the two A&B TDEM soundings are given in Appendix B.

4.0 INTERPRETATION RESULTS

4.1 General

The main objective of TDEM soundings is to derive the resistivity layering (geoelectric section) of the subsurface. The translation of resistivity layering into hydrologic information is generally accomplished by two methods. These include:

1) Using available knowledge about the relation between resistivity values and local hydrology. From more than twenty previous TDEM surveys on the Hawaiian Islands, it has been observed that volcanic rocks saturated with salt water exhibit resistivities typically less than 5 ohm-meters (ohm-m). Conversely, unweathered volcanic rocks that are dry or fresh water saturated exhibit high resistivities (generally greater than 500 ohm-m). Weathered volcanics or ash flows and intrusives often exhibit intermediate resistivities (about 10 ohm-m to 100 ohm-m).

   Applying this knowledge, characteristic ranges of resistivities expected for the local hydrogeologic units at the Kailua study area are shown in Figure 4-1. It is noted that some overlap in resistivity values occur and in these cases, other factors are used to infer the geologic/hydrologic unit in question. For example, a low resistivity unit (i.e., less than 10 ohm-m) occurring at an elevation above sea level is assumed to be caused by either weathered rock units or intrusives instead of salt water saturated formations.

2) Calibration of the geophysical interpretation at a well. In this case, no wells were available for comparison in the Kailua area.

Where a conductive layer (less than 5 ohm-m) is detected below sea level in the TDEM measurement, it is interpreted to be caused by salt water saturated volcanics. Static fresh water levels can be calculated from these soundings by using the Ghyben-Herzberg relation illustrated in Figure 4.2. The Ghyben-Herzberg relation states that for every one foot of fresh water above sea level, approximately 40 ft of fresh water will exist below sea level assuming hydrostatic equilibrium.

4.2 Geoelectric Cross Section

The results of the inversion of the individual TDEM soundings is the 1-D resistivity layering as a function of depth. The TDEM results from individual soundings can be linked together to produce a 2-D geoelectric cross section along a survey transect. The geoelectric cross section can be correlated to geologic units by comparison with available geologic information. One geoelectric cross section was produced from the two soundings acquired at the Kailua study site.

Cross Section A-A′

Figure 4-3 shows the results of the two TDEM soundings presented as a north to south trending geoelectric cross section, in which layers that exhibit similar resistivity values have been linked together.

The upper layer (green) of the cross section, displays resistivities ranging from 43 ohm-m to 46 ohm-m. This layer is interpreted to represent weathered surface volcanics which range in thickness from about 100 to 120 ft. The middle layer, with resistivities ranging from 1320 to 1702 ohm-m, is interpreted to represent dry unweathered volcanics above sea level and where it occurs below sea level, it is expected to be saturated with fresh/brackish basal mode water. The lower layer beneath both soundings (blue) exhibits a resistivity of 2.5 ohm-m and this layer is interpreted to represent salt water saturated volcanics. The approximate thickness of the fresh/brackish water lens is 199 ft below Sounding 1 and 210 ft below Sounding 2.

4.3 Hydrogeologic Interpretation

TDEM soundings at the Kailua study site detected salt water saturated volcanics below sea level. The fresh/brackish water resource can be estimated in these soundings by the volume between sea level and the interpreted elevation of salt water, plus head calculated from the Ghyben-Herzberg relation. Table 4-1 shows the thickness of the fresh/brackish water lens interpreted directly from the model results for each sounding.

TABLE 4-1
HYDROGEOLOGIC INFORMATION
DERIVED FROM TDEM SOUNDINGS

Sounding # (Year)	Surface Elevation (ft)	Approximate Thickness of Fresh/Brackish Water Lens (ft)
1 (1998)	840	204
2 (1998)	970	215

The accuracy of determining the depth to sea water from TDEM soundings is estimated to be ±5% of the total depth calculated in the sounding results (e.g., from ground surface to sea water).

5.0 CONCLUSIONS AND RECOMMENDATIONS

The results of the TDEM surveys in the vicinity of Kailua, Maui indicate that a relatively thick basal water resource occurs beneath this portion of the island. The thickest zone of potential fresh/brackish basal water is interpreted to occur beneath Sounding 2, and it is estimated to be 215 ft. The results of the surveys are shown in Figure 4-3. Sounding 1, located approximately 1200 ft downslope from Sounding 2, shows near identical results to Sounding 2. No high-level ground water resources were detected in the TDEM soundings.

Above Sounding 2, the potential for high-level ground water may exist if ground water damming structures (i.e., dikes, ring fracture) are present in the subsurface. No soundings were made at the higher elevations where damming structures may exist.

References

1. Davis, S. N., DeWiest, R. J. M., 1966. Hydrogeology: Ground water in igneous rocks. pp. 333-343.
2. Stearns, H. T., Macdonald, G. A., 1942. Geology and ground-water resources of the Island of Maui, Hawaii: Hawaii Division of Hydrography Bulletin 7, pp. 61-81.
3. Takasaki, K. J., 1972. Preliminary report on the water resources of central Maui: Hawaii Division Water and Land Development, Circ. C62, pp. 9-29.
4. Wilt, M. J., 1991. Interpretation of time domain electromagnetic soundings near geologic contacts, Ph.D. Thesis, Lawrence Berkeley Laboratory, University of California Earth Sciences Division. pp. 185.

Potential Water Source Development for A&B's 63-Acre Residential Project in Haliimaile, Maui

Prepared for:

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Prepared by:

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Honolulu, Hawaii 96813

Hearing starts at
HOOL → JULY 30th ⇨ Sandalwood G.C.

WTP/A&B
for WTP
8½ → 7MGD + 1½ for
Kula AG PARK

June 1998

Introduction

This brief report discusses the development of new potable water supply for the proposed residential development on TMK 2-5-03:Portion 10 in Haliimaile, Maui. The 63-acre project will consist of 196 single-family residential units, 10 acres of park, and 9 acres of roads, some of which will include 40-foot wide landscape buffers. Approximate potable water requirements for the project, based on DWS standards, are as follows:

	Average Demand (GPD)	Maximum Demand (GPD)
Residential (196 Units @ 600 GPD/Unit)	117,600	176,400
Parks (10 Acres @ 1700 GPD/Acre)	17,000	25,500
Roadway Landscape Buffer (7 Acres @ 1700 GPD/Acre)	11,900	17,850
Total	146,500	219,750

The Maui County Department of Water Supply (DWS) system serving the Haliimaile area is supplied by surface water pumped from the East Maui Irrigation (EMI) Company's Wailoa Ditch. This surface water source is treated to drinking water quality at DWS' Kamole Water Treatment Plant. However, the amount of water extracted for potable use from Wailoa Ditch is fully committed. New source development will be required to serve the proposed project. This source could either be a new well developed within the system's service area or a well located elsewhere which would deliver additional supply to Wailoa Ditch.

Potential Well Development

A&B Properties is in the process of evaluating the development of a potable quality well above the community of Kailua in East Maui. A small portion of its supply, less than 50,000 GPD, would be utilized in Kailua to replace water now supplied from a shallow development tunnel above the Wailoa Ditch. The balance of the well's supply, if delivered into Wailoa Ditch, would be available for other A&B projects in the service area of the Kamole Water Treatment Plant, including the 63-acre project in Haliimaile.

Well Sites Being Considered. The two sites shown on Figure 1 are being considered for well development. The lower site is at an elevation of 840 feet and is just makai of the forest reserve boundary. The upper site is at 920-foot elevation and is adjacent to the small tank which currently supplies Kailua.

220,000 @1.5 → 330,000

.33 x 700 ⇒

2100
2100
231.00 GPM for 0.33 MGD

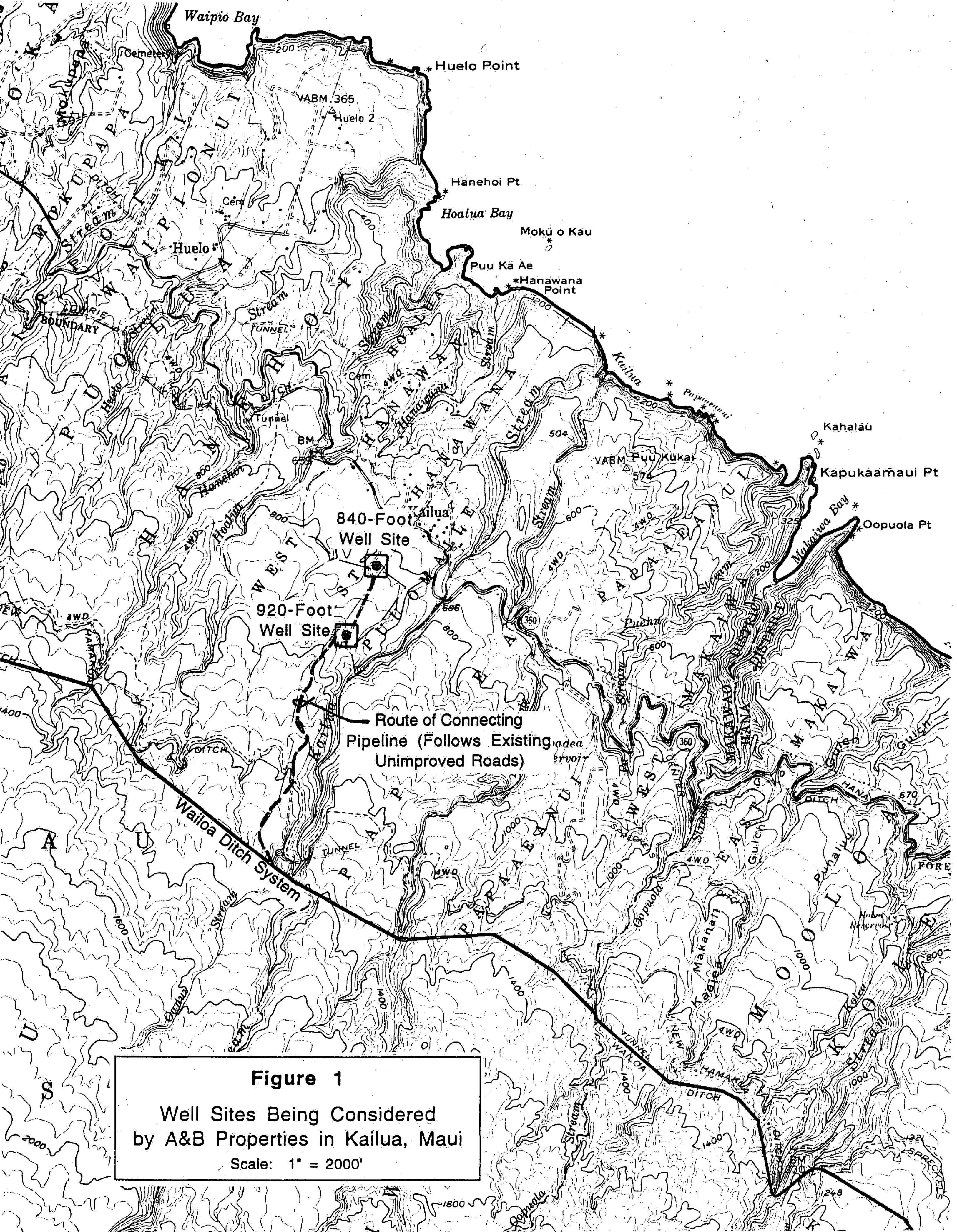


Figure 1

Well Sites Being Considered by A&B Properties in Kailua, Maui

Scale: 1" = 2000'

Hydrogeologic Circumstances at the Proposed Well Sites. Since no wells have previously been developed in the Kailua area, initial site selection was based on surficial geology, field reconnaissance, and general knowledge of the water bearing properties of these rocks. This information suggests the following:

- For about the first 100 to 150 feet, the borehole would be expected to penetrate the poorly permeable Kula lavas.

- The contact between younger Kula and older Honomanu lavas will be transitional rather than sharply distinct. These transitional lavas are of unknown thickness.

- Substantially above sea level, the borehole should penetrate the permeable rocks of the Honomanu volcanic series.

- High level groundwater perched on the transitional lavas between the two formations may be encountered. However, the yield of this perched source is likely to be quite small, probably not sufficient for Kailua and certainly not adequate for the larger quantities of water that would need to be delivered to Wailoa Ditch. As such, the well would be designed so that no water from this level would be utilized.

- At a short distance above sea level, a basal lens of potable quality water in the permeable Honomanu lavas will be encountered. This is the aquifer that the well would be designed to tap. The ~~This~~ limit on the amount of water that can be safely extracted without compromising its potable quality is a function of the amount of natural groundwater flow in this location and the formation's permeability. This can only be determined by drilling and pump testing.

Geophysical Survey Results. To further evaluate hydrogeologic conditions prior to undertaking the relatively expensive process of actual drilling, time domain electromagnetic (TDEM) geophysical surveys were performed at the two possible well sites. The work was recently completed by Blackhawk Geometrics, a mainland firm based in Golden, Colorado. The TDEM process resolves the underlying strata into layers of similar electrical conductance. It is able, with the assistance of computer optimization techniques, to determine thicknesses of each of these layers which best fit the field measurements. This technique has proven particularly effective where the stratigraphy is uninterrupted by intrusive structures (such as dikes) and groundwater occurs as a basal lens. Volcanics saturated with saline groundwater which lie below the fresh basal lens are highly conductive. The conductivity contrast is at least two but more often three orders of magnitude greater than unsaturated volcanics or volcanics saturated with fresh water. When the depth of saline groundwater below sea level is determined, it also establishes the thickness of the basal lens below sea level and, through the Ghyben-Herzberg principle, the height of the lens above sea level.

Blackhawk's final report on the TDEM survey results is not yet available, but its preliminary analysis of the data has been done and can be summarized as follows:

- The field data at both potential well sites best fit a three-layer model of the stratigraphy: an upper, moderately conductive layer; a highly conductive basement layer of saline groundwater below sea level; and a highly resistive intervening layer. No anomalies, such as would be created by the presence of intrusive structures, were found.

- At both sites, the moderately conductive surface layer was determined to be about 150 feet thick. Although this is about the thickness expected for the younger Kula lavas, its electrical resistivity suggests that it is weathered volcanics (ie. sapprolite) rather than unweathered flow lavas.

- At the 840-foot potential well site, the highly conductive layer, interpreted to be volcanics saturated with saline groundwater, was determined to begin 200 feet below sea level. Based on the Ghyben-Herzberg relationship, this suggests that the top of the lens is five feet above sea level in this location.

- At the upper, 920-foot site, the top of saline groundwater was found to be 220 feet below sea level. This implies a basal head of 5.5 feet and is in accord with the expected increase in the thickness of the lens with distance inland. The lower site is 5600 feet from the shoreline whereas the upper site is 7000 feet.

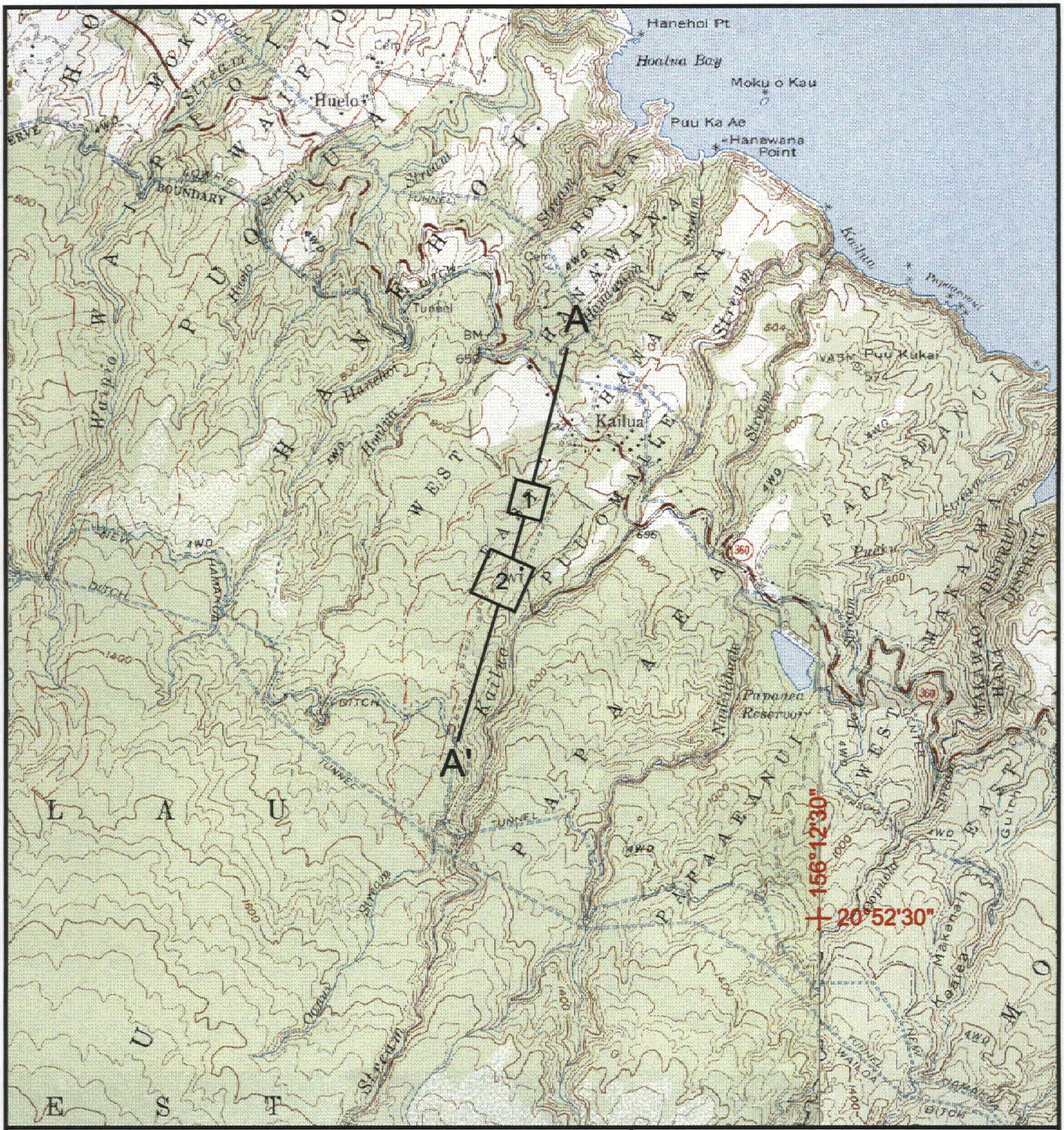
Prospects for Successful Well Development

Since the lower permeability Kula lavas do not function as a caprock at the shoreline, basal groundwater discharges into coastal waters directly from the permeable Honomanu lavas. For this circumstance, thicknesses of the basal lens determined by the TDEM survey at locations just 1.1 and 1.3 miles from the shoreline can only be maintained by a substantial groundwater flux. Based on formation permeability in the range of 1000 to 2500 feet per day and the gradients suggested by the basal heads, flowrates of 5 to 12 MGD per coastal mile are calculated. Although this information does not directly translate to safe pumping rates, experience with similar circumstances elsewhere suggests that safe pumping rates of 0.7 to 1.0 MGD may be possible at the lower site and perhaps 1.0 to 1.4 MGD might be possible at the higher site. These rates are considerably greater than required to supply Kailua and the proposed 63-acre residential project in Haliimaile.

Well Development Costs

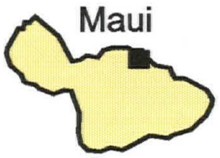
An estimate of the construction costs, based on the development of a 14-inch well at 920-foot elevation, installation of a 1000 GPM (1.4 MGD) pump, and construction of a 0.10 MG storage tank and 12-inch connecting pipeline to Wailoa Ditch, has been prepared and is summarized in the tally below. Total project cost, including engineering and contingency, is estimated to be $1,930,000.

	Dollars
Drill, Case, and Pump Test 14-Inch Well	545,000
1000 GPM Line Shaft Pump and Appurtenances	320,000
0.10 MG Storage Tank and Related Site Work	290,000
Electrical	295,000
Connecting 12-Inch HDPE Pipeline	230,000
Total for Construction	1,680,000
Engineering and Contingency	250,000
Project Total	1,930,000



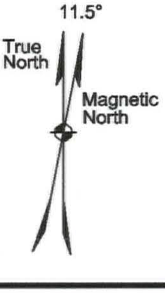
Explanation

1	TDEM Soundings
A-A'	Section Line



Survey Location

0 2000
Scale in Feet
Contour Interval 40 Feet



BLACKHAWK GEOMETRICS

Location Map
TDEM Soundings

A&B Properties, Inc.

Kailua, Maui, Hawaii

Project No. 9818 Figure: 1-1

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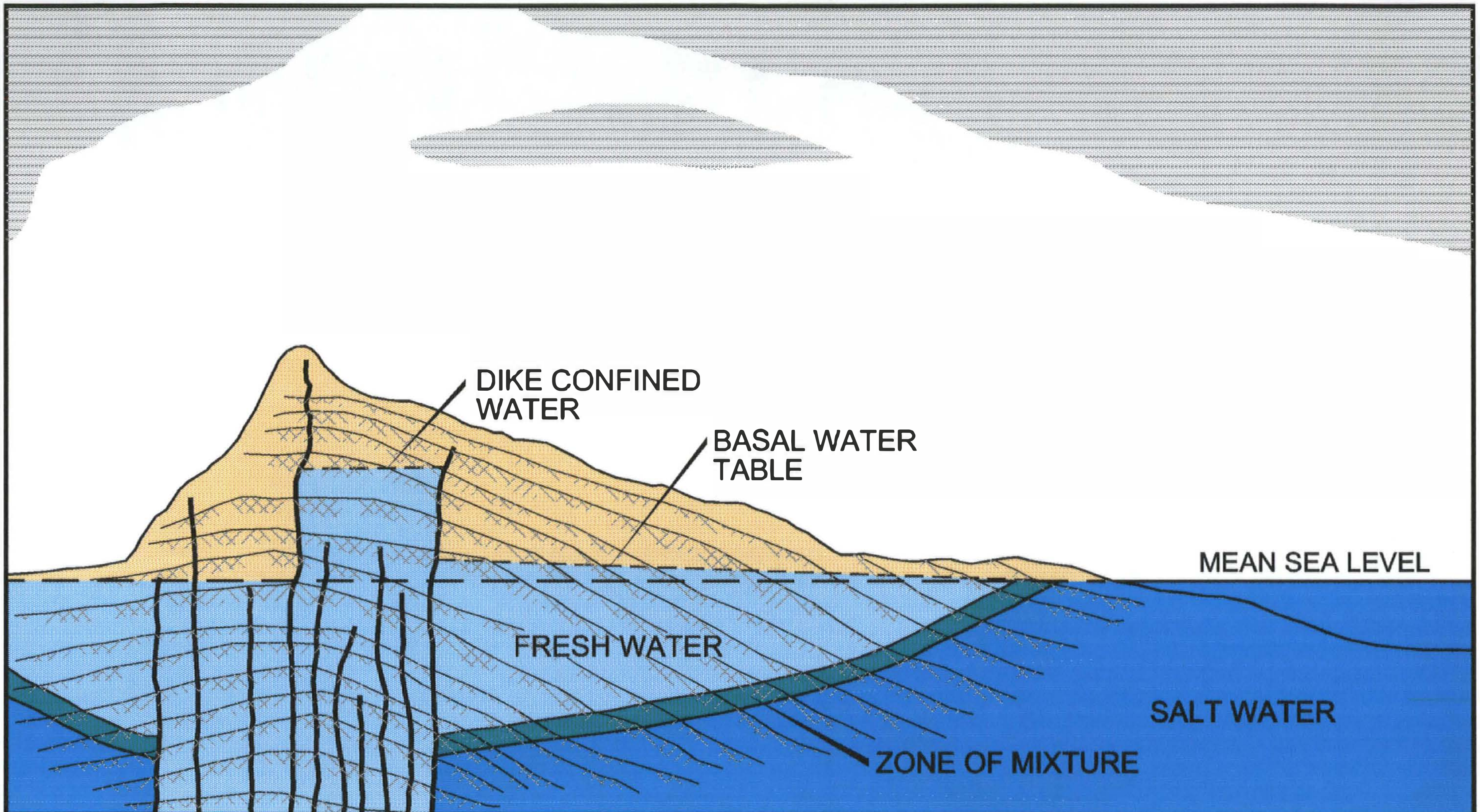

BLACKHAWK GEOMETRICS

Schematic
Hydrogeologic Cross Section

A&B Properties, Inc .
Kailua, Maui, Hawaii

Project No. 9818	Figure: 1-2

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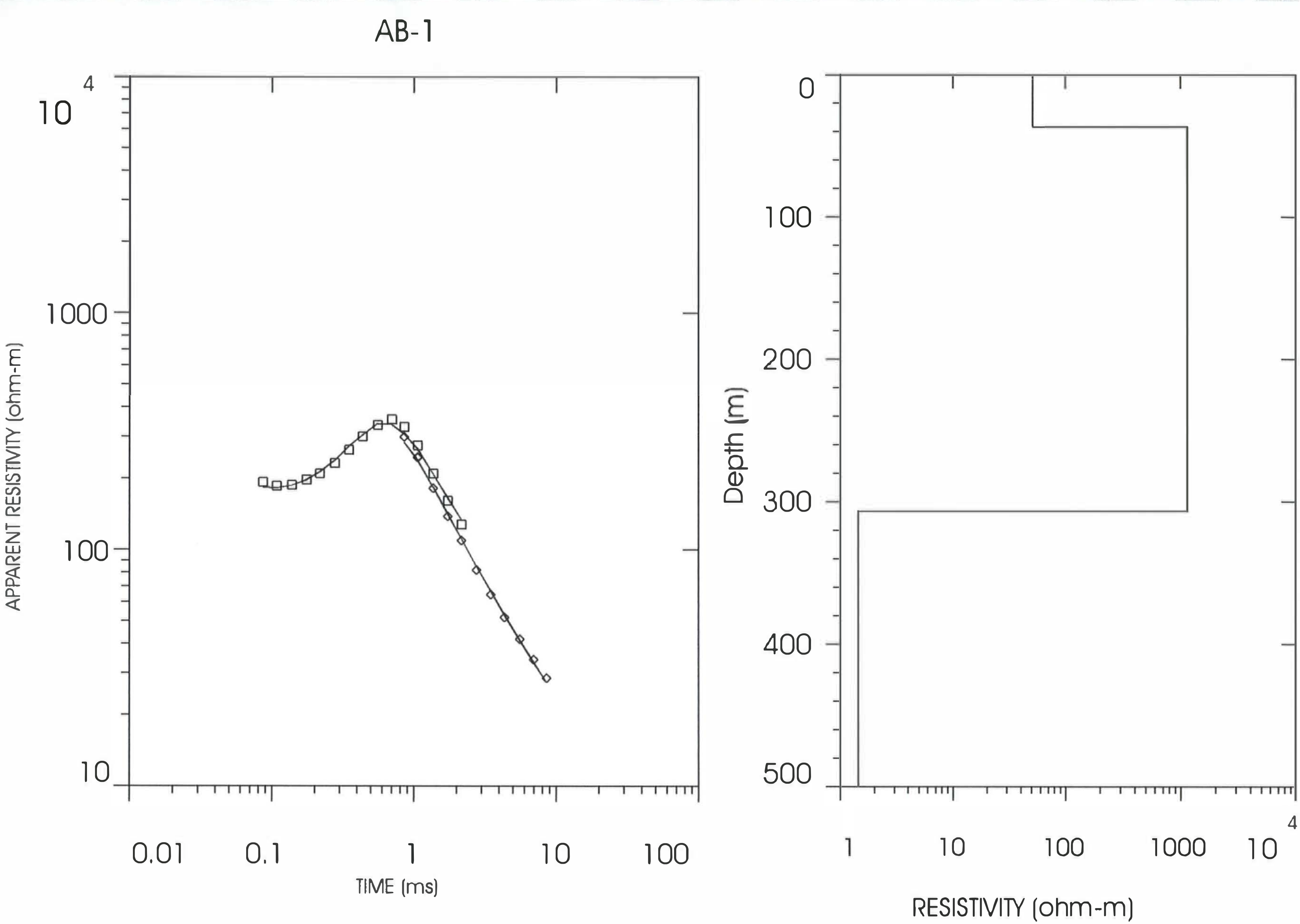

BLACKHAWK GEOMETRICS

TDEM Inversion Results
Sounding AB-1
A&B Properties, Inc.
Kailua, Maui, Hawaii

Figure: 3-1

Project No. 9818

\projects\maui98\9818a&b\Results1.cdr

DATA SET: AB-1

CLIENT:	A&B PROPERTIES, INC	DATE:	05-10-98
LOCATION:	KAILUA, MAUI	SOUNDING:	1
COUNTY:	MAUI	ELEVATION:	256.00 m
PROJECT:	KAILUA WATER WELLS	EQUIPMENT:	Geonics PROTEM

LOOP SIZE: 152.000 m by 152.000 m AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y) TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 1.0000 N: 1.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 4.912 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	CONDUCTANCE (Siemens)
			256.0	
1	51.09	36.52	219.4	0.714
2	1151.0	270.0	-50.60	0.234
3	1.44			

ALL PARAMETERS ARE FREE

CURRENT: 19.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 7 RAMP TIME: 110.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	37351.7	39939.4	-6.92
2	0.108	22679.8	23345.8	-2.93
3	0.138	12174.2	12185.7	-0.0949
4	0.175	6205.1	6217.8	-0.205
5	0.218	3268.7	3188.6	2.45
6	0.278	1535.6	1473.1	4.06
7	0.351	704.9	664.8	5.67
8	0.438	332.6	324.9	2.32
9	0.558	153.7	150.7	1.94
10	0.702	80.01	85.89	-7.35
11	0.858	53.94	59.55	-10.39
12	1.06	41.15	43.15	-4.87
13	1.37	33.10	33.07	0.108
14	1.74	27.07	25.82	4.61
15	2.17	22.03	20.38	7.51

CURRENT: 19.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 110.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
16	0.857	62.34	67.35	-8.04
17	1.06	48.92	50.63	-3.50
18	1.37	40.89	40.28	1.50
19	1.74	33.88	32.73	3.40
20	2.17	27.77	26.96	2.92
21	2.77	23.16	21.87	5.56
22	3.50	18.59	17.63	5.18
23	4.37	14.84	14.33	3.46
24	5.56	11.20	11.27	-0.605
25	6.98	8.54	8.91	-4.28
26	8.56	6.69	7.11	-6.27

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	P 3	T 1	T 2
P 1	0.88				
P 2	-0.01	0.06			
P 3	0.05	-0.06	0.56		
T 1	-0.14	-0.08	0.08	0.82	
T 2	0.02	0.01	-0.04	0.03	0.99

BLACKHAWK GEOMETRICS

TDEM Inversion Results
Sounding AB-1
A&B Properties, Inc.
Kailua, Maui, Hawaii

Figure: 3-2

Project No. 9818

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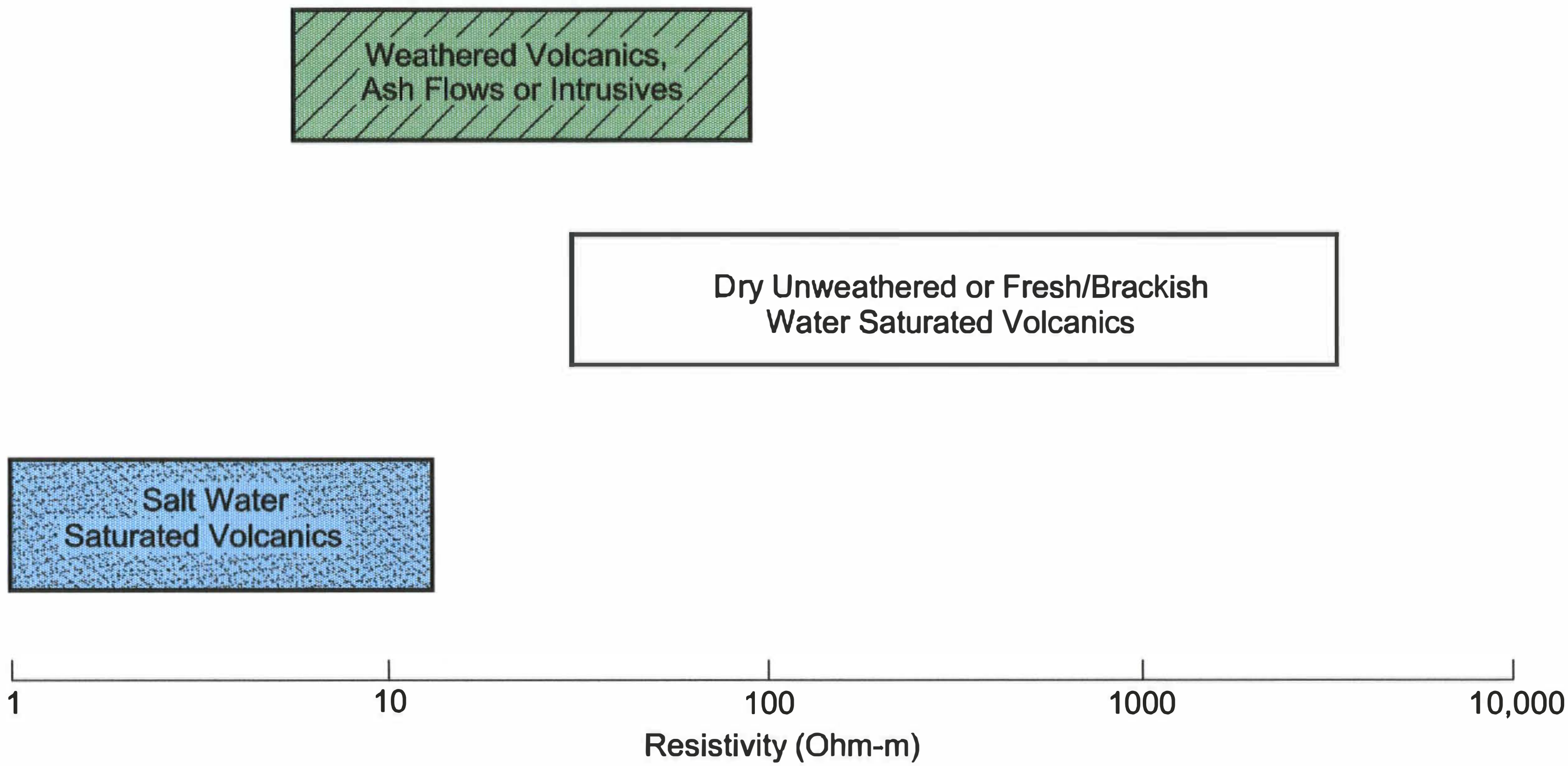

BLACKHAWK GEOMETRICS

Characteristic Resistivity Ranges

A&B Properties, Inc .
Kailua, Maui, Hawaii

Project No. 9818 Figure: 4-1

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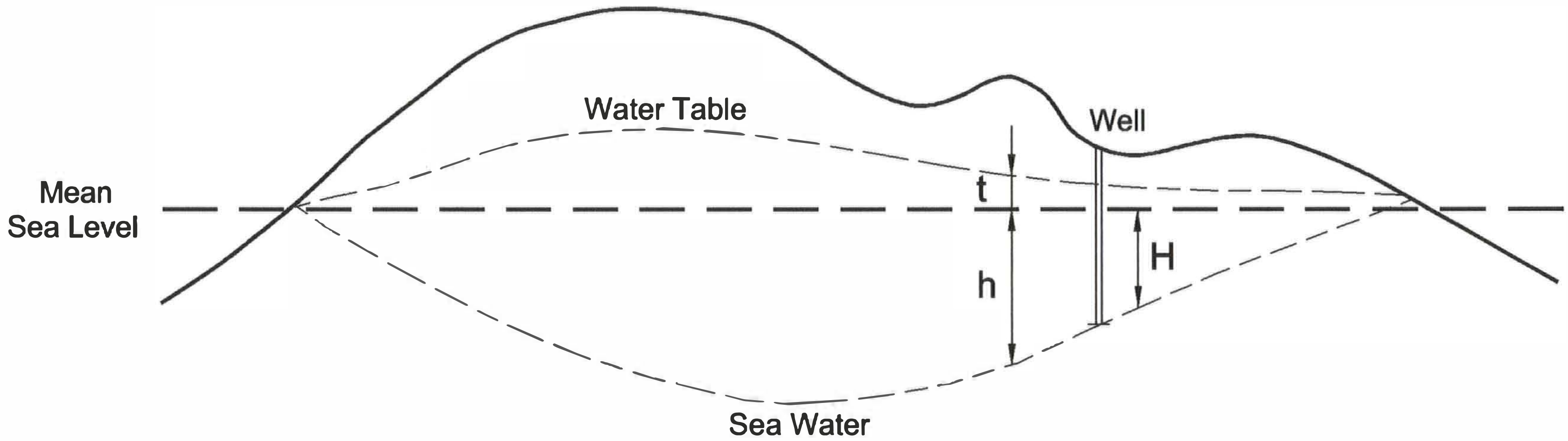

$$t = 1/40\ (h)$$

From: Herzberg

BLACKHAWK GEOMETRICS

Illustration of the Ghyben-Herzberg Principle

A&B Properties, Inc .
Kailua, Maui, Hawaii

Project No. 9818 Figure: 4-2

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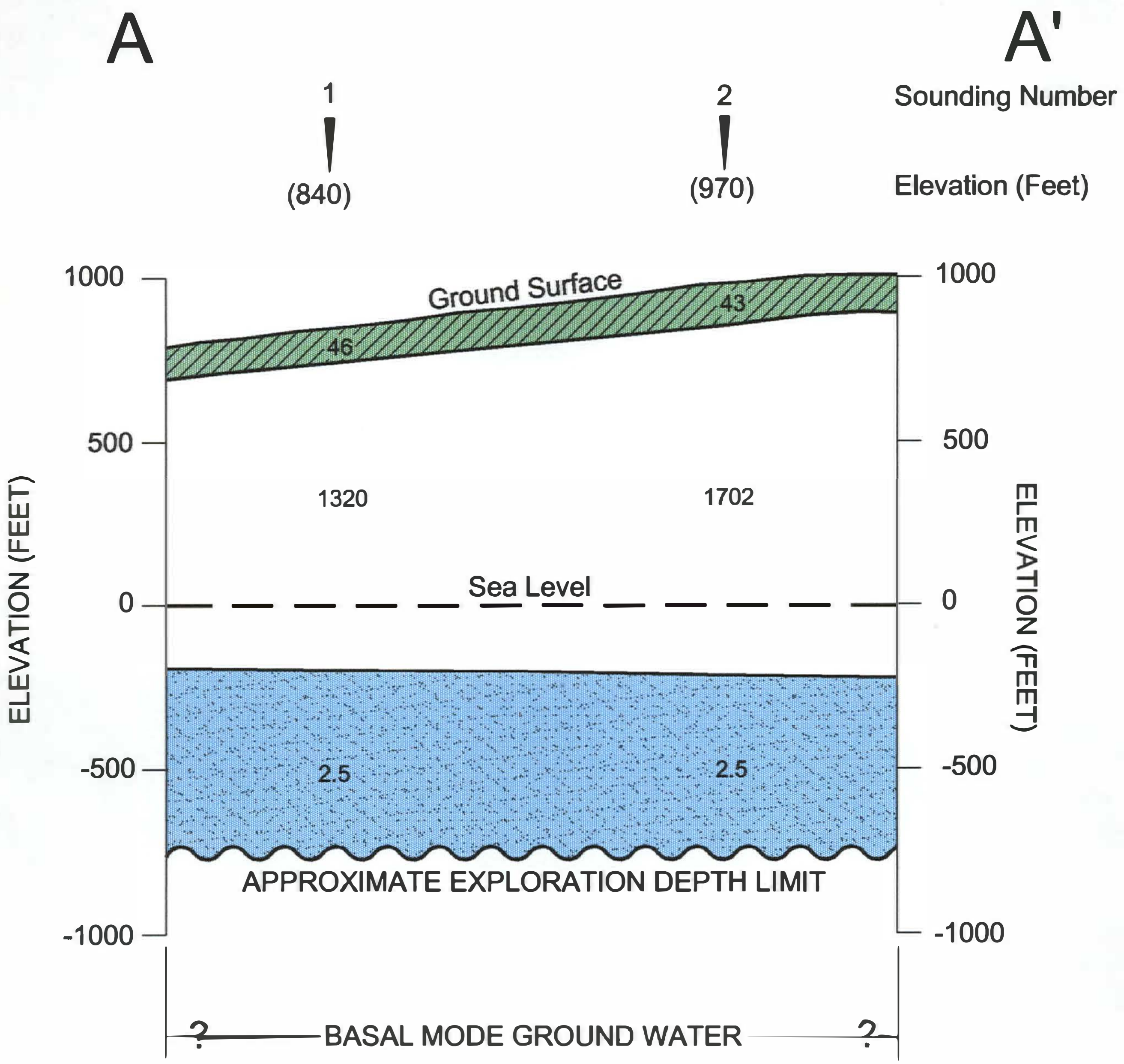

Explanation

43 — Resistivity in ohm-m

Dry unweathered or fresh-brackish water saturated volcanics

Weathered volcanics at surface or inferred structure (possible ash flows, or intrusives) at depth

Salt water saturated volcanics

500 ft.
0
500 ft.
Scale in Feet

BLACKHAWK GEOMETRICS

Geoelectric Cross Section A-A' Kailua Study Site

A&B Properties, Inc

Kailua, Maui, Hawaii

Project No. 9818 — Figure: 4-3

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Case Histories of Time-Domain Electromagnetic Soundings in Environmental Geophysics

Pieter Hoekstra and Mark W. Blohm**

Abstract

Time-domain electromagnetic (TDEM) soundings are a surface electromagnetic technique that finds increasing use in environmental geophysics. Commercial equipment is now available for TDEM soundings in the exploration depth range from about 5 m to about 5000 m. Application of TDEM is illustrated in three case histories.

The transmitter-receiver array used in all three investigations was the central-loop array, in which measurements of the electromotive force due to the vertical magnetic field are made with a receiver in the center of square, nongrounded transmitter loops. The dimensions of the transmitter loops were varied from 30 m by 30 m for effective exploration depths between 5 m to 75 m, to 500 m by 500 m for effective exploration depths to about 2500 m. These relatively small dimensions of receiver/transmitter arrays, compared to the exploration depth, allow TDEM surveys to be made in urban areas where open spaces are limited in size, and where environmental and ground-water problems are perhaps most urgent. Also, the procedures of signal processing used in TDEM facilitate operation in the presence of high ambient electrical noise prevalent in urban settings.

The three case histories map:

(1) the depth of first occurrence of brine for assisting site evaluation of a high-level nuclear-waste repository in bedded salts near Carlsbad, New Mexico,

(2) the encroachment of salt water in a multiple-zone coastal aquifer system in the Salinas Valley, California, (The availability of about 100 monitoring wells allowed correlation of formation resistivities to ground-water salinity.) and

(3) shallow basalt flows in the exploration depth range from 5 m to 30 m. (This case history shows the results of TDEM measurements over the time range from about 10^{-6} s to 10^{-4} s with central-loop soundings of small (30 m) dimensions.)

Introduction

Time-domain electromagnetic (TDEM) soundings increasingly are being employed for determining geoelectrical sections. Reported applications of this TDEM method are in mapping of volcanic cover (Frischknecht and Raab, 1984; Keller et al., 1984), onshore and offshore permafrost (Ehrenbard et al., 1983), geothermal reservoirs (Fitterman et al., 1988), hydrocarbons (Rabinovich et al., 1977; Wightman et al., 1983), and ground water (Fitterman and Stewart, 1986; Mills et al., 1988). Theoretical aspects of the method, such as behavior of magnetic and electric fields (e.g., Nabighian and Oristaglio, 1984), definition of apparent resistivity (Kaufman and Keller, 1983; Spies and Eggers, 1986), transmitter-receiver arrays (Kaufman and Keller, 1983), and influence of two-dimensional (2-D) and three-dimensional (3-D) structures on one-dimensional interpretations (Hohmann, 1988; Newman et al., 1987) are discussed throughout the geophysical literature [see also McNeill, Vol. I—Ed.].

Several reasons are apparent for the increasing use of TDEM in environmental geophysics. In urban areas ambient electrical noise is high, and open spaces limited. TDEM surveys can often work around these limitations. Small transmitter-receiver arrays can be laid out in athletic fields, parks, and other open spaces, and ambient

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electrical noise due to residential power service can often be removed by stacking. Also, recent availability of equipment with fast, current ramp turn-off and early-time measurements bring shallow mapping objectives for ground-water protection and contaminant investigations within the exploration depth range of TDEM.

A limitation of TDEM at this time is the lack of practical, cost-effective algorithms for interpreting 2-D and 3-D structures. At present, forward modeling of 2-D and 3-D structures (Newman et al., 1987), requires significant central processing unit (CPU) time on the mainframes negating their application to shallow TDEM exploration. It is in the development of practical algorithms for 2-D and 3-D interpretations for personal computers that the main advances in TDEM must come.

Illustrated applications of the method to three environmental objectives include (1) assisting in siting of high-level, nuclear-waste repositories, (2) mapping the intrusion of salt water in coastal aquifers, and (3) mapping the thickness of thin basalt flows. The basic principles of the equipment and the procedures of data acquisition and processing are similar for all three case histories. Some characteristics of central-loop array measurements, such as land survey requirements, location of plotting points, and vertical resolution are reviewed briefly. Equipment design parameters and data acquisition, processing, and interpretation procedures are discussed. These principles are illustrated subsequently on the three case histories. The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories.

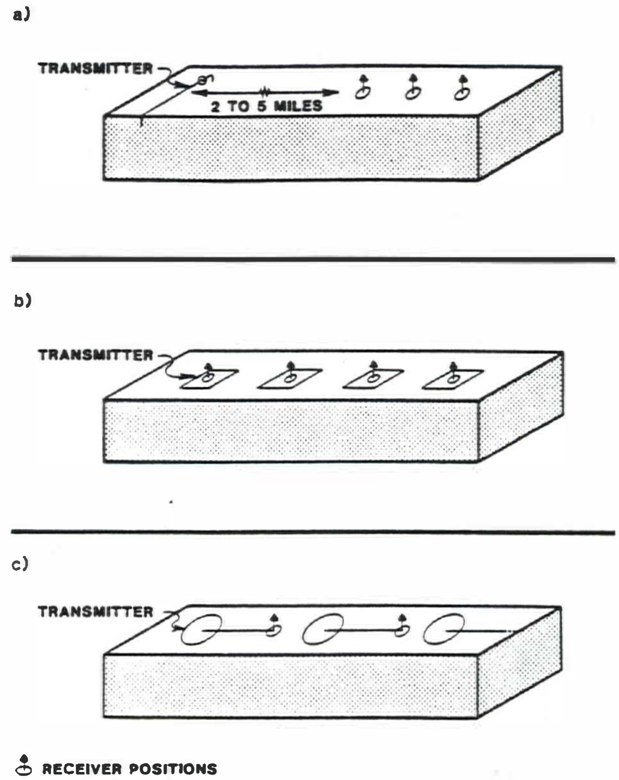

FIG. 1. Transmitter-receiver arrays, (a) grounded line, (b) central loop, and (c) loop-loop.

Practical Aspects of Data Acquisition

Transmitter-Receiver Arrays

The three types of transmitter-receiver arrays employed in TDEM soundings are illustrated in Figure 1. The array used in the three case histories is the central loop array (Figure 1b). For applications in environmental geophysics there are certain advantages to the central loop array, such as:

(a) Land survey and space requirements.—Figure 2 shows the measured behavior of the electromotive forces (emf's) due to horizontal (x) and vertical (z) magnetic field components on a profile through the center of a square transmitter loop at 2.2 ms after current turn-off. Data at other times would show a similar behavior but differ in amplitudes. The emf due to the z-component can be seen to be relatively flat about the center. Location errors of $\pm 10\%$ L (L is side of square) cause negligible errors, and deviations from a square transmitter loop have little effect on a data set. Because in central loop soundings the geoelectric section is derived from emf$_z$, requirements for accurate positioning are minimal which enhances the practical value of field survey productivity, and allows flexibility in choosing a station location. Because emf$_x$ has a zero crossing in the center of the loop, its measurement would require careful survey control. Also, ambient electrical noise is higher in horizontal components.

The dimensions of transmitter loops in central-loop arrays depend on required exploration depth, exploration objective, and geoelectric section. Optimum dimensions are generally selected from forward modeling and field tests. Typically, the length of a side of the transmitter loop is about two-thirds of the exploration depth for the EM-37. The EM-42 is generally employed for exploration depths from about 300 m to 2500 m with 500 m by 500 m transmitter loops, and with a grounded line array for deeper objectives.

The grounded line array (Figure 1a) with long offset receiver locations is dominantly used in deep electrical soundings in support of oil and gas exploration (Keller et al., 1984). The loop-loop array (Figure 1c) finds ap-

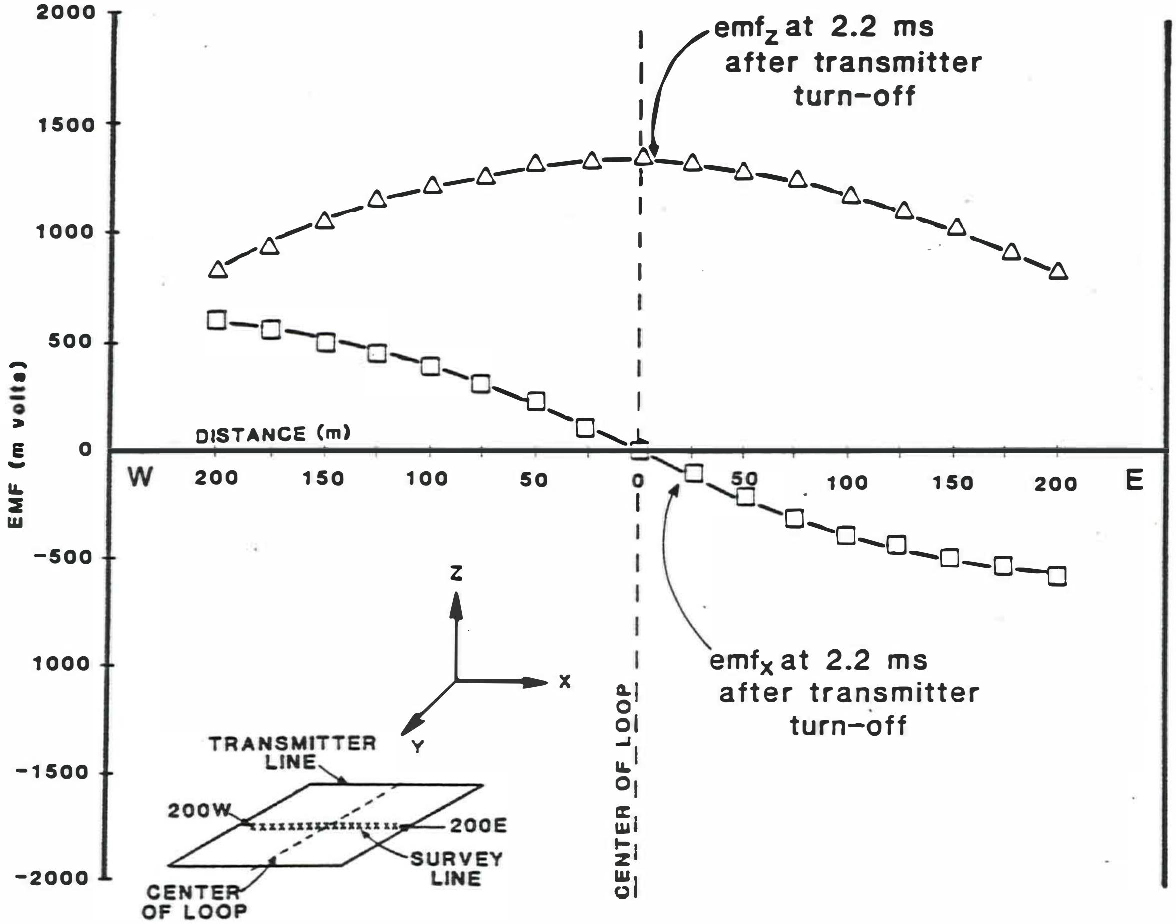

FIG. 2. Measured behavior of the electromotive forces due to vertical (emf_z) and horizontal (emf_x) magnetic fields on a profile through the center of a square transmitter loop.

plication in mineral exploration and in mapping of fractures and shear zones.

(b) Well-defined sounding plotting points.—The behavior of induced eddy currents and the resulting behavior of the secondary magnetic fields in horizontally-layered media are well documented (Kaufman and Keller, 1983; Ward and Hohmann, 1988). They show a current distribution diffusing downward and outward from the source. For nongrounded, square-loop transmitters currents are symmetrically distributed about the center. Therefore, the center is a well-defined plotting point.

In the grounded-line array or loop-loop array the entire section between transmitter and receiver is expected to influence the measurements, although subsurface conditions near the receiver may have a larger influence on emf_z measured. The correct plotting point of a station is not well defined. Some place the plotting point below the receiver (Keller et al., 1984) and others midway between the transmitter and receiver (Rabinovich and Surkov, 1978). This same situation prevails in loop-loop arrays. In frequency-domain loop-loop arrays the midpoint of the array has traditionally been used as the plotting point.

(c) Vertical resolution.—Kaufman and Keller (1983) show that (1) the asymptotic behavior of emf_z at late time, is given by

$$emf_z = \frac{\mu^{5/2}}{4\pi^{3/2}} \frac{\sigma^{3/2} M_t M_R}{t^{5/2}}; \tag{1}$$

where

t = time after current turn-off,
σ = conductivity of uniform half-space,
μ = magnetic susceptibility,
M_t = moment of transmitter,
M_R = moment of receiver;

and (2) that this asymptotic expression describes the emf over the time range given by;

$$\frac{\tau}{R} > 16, \tag{2}$$

where

$$\tau \text{ is } \sqrt{\frac{8\,\pi^2 t}{\mu_0\,\sigma}}.$$

Figure 3 is a nomograph showing the onset of "late stage" behavior ($\tau/R > 16$), as a function of resistivity, and time at several values of R. Also shown on Figure 3 are the time ranges of measurement for the three systems used in the case histories. In central loop soundings typical values of R are between 15 m and 250 m, so that over a large time range of measurements emf$_z$ is proportional to $\sigma^{3/2}$. This high sensitivity of the quantity measured (emf$_z$) to the geoelectric section often results in a reduced range of equivalence for certain sections compared to other electrical and electromagnetic techniques (Fitterman et al., 1988).

Equipment

The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories. All three sets of equipment use the current waveform illustrated in Figure 4, consisting of equal periods of time-on and time-off. Figure 5 illustrates the difference in data acquisition between the EM-47 and EM-37, and the EM-42. In the EM-47 and EM-37 an analog stack is performed, and after completion of the stacking and A/D conversion, the data are stored in solid state memory. Normally, at the completion of a survey day, the data are transfered to a computer for data processing, plotting, and interpretation. During field operations no real-time processing is available. Minimum detectable signal in typical, urban, ambient-noise environments is 10^{-9} V/A-m^2 (normalized by current in transmitter loop, and effective area of receiver coil).

In the EM-42 the transient is sampled at 400 μs intervals, and these samples are digitally stored on 1/2-inch, 9-track tape. "Smart stacking" is applied to the data in real time. The minimum detectable signal with

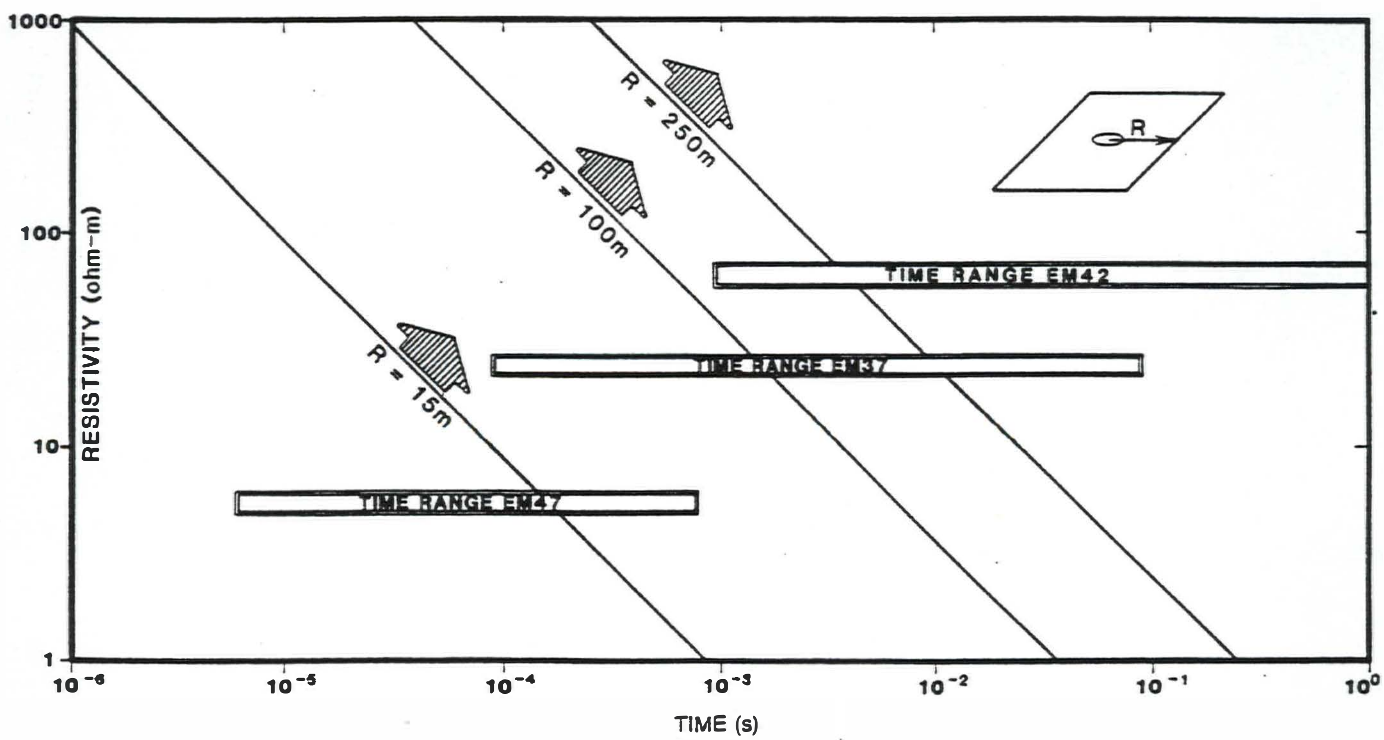

FIG. 3. Nomograph showing onset of late stage behavior for central-loop array as a function of time and resistivity of uniform half-space.

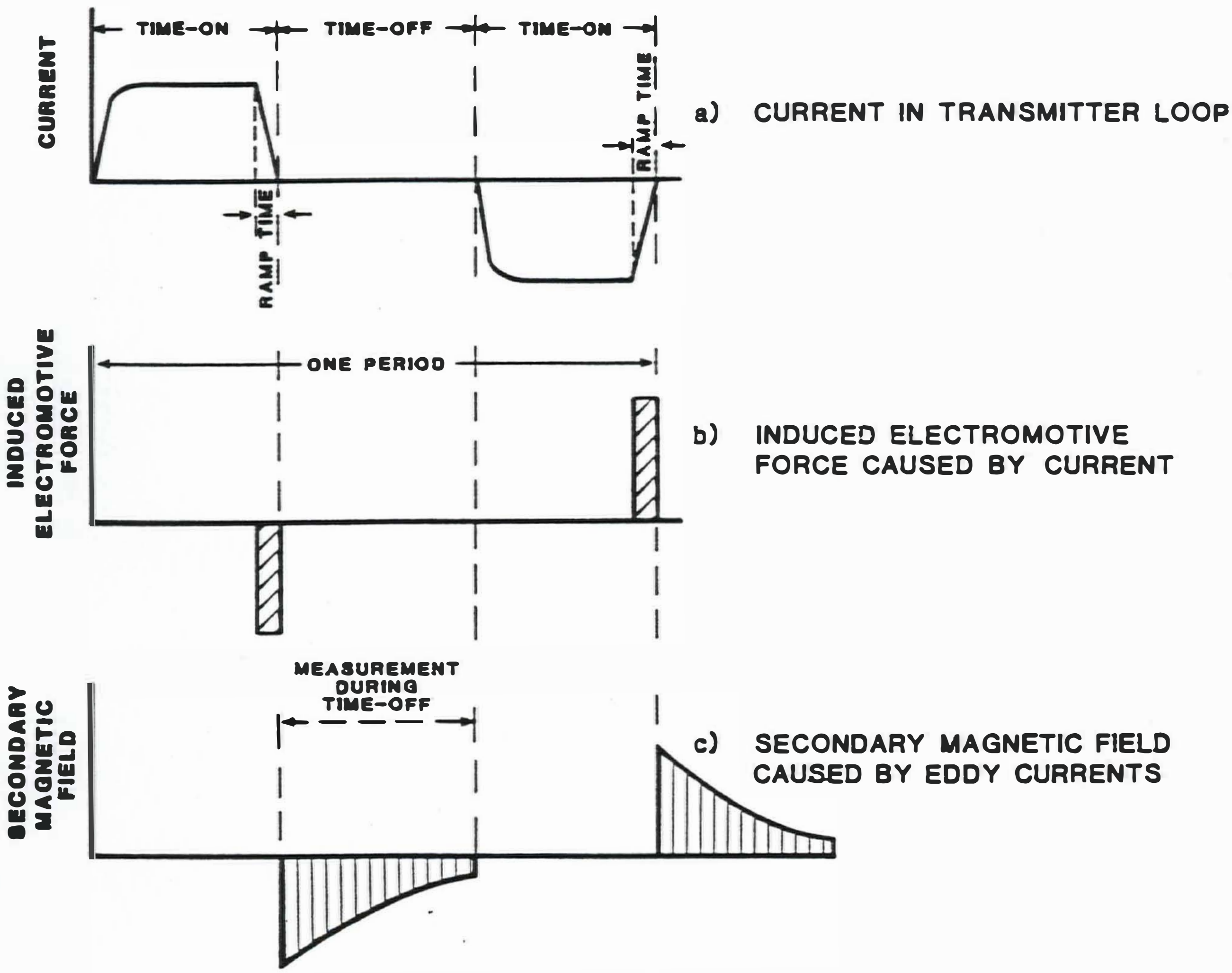

FIG. 4. System waveforms employed in Geonics EM-47, EM-37, and EM-42.

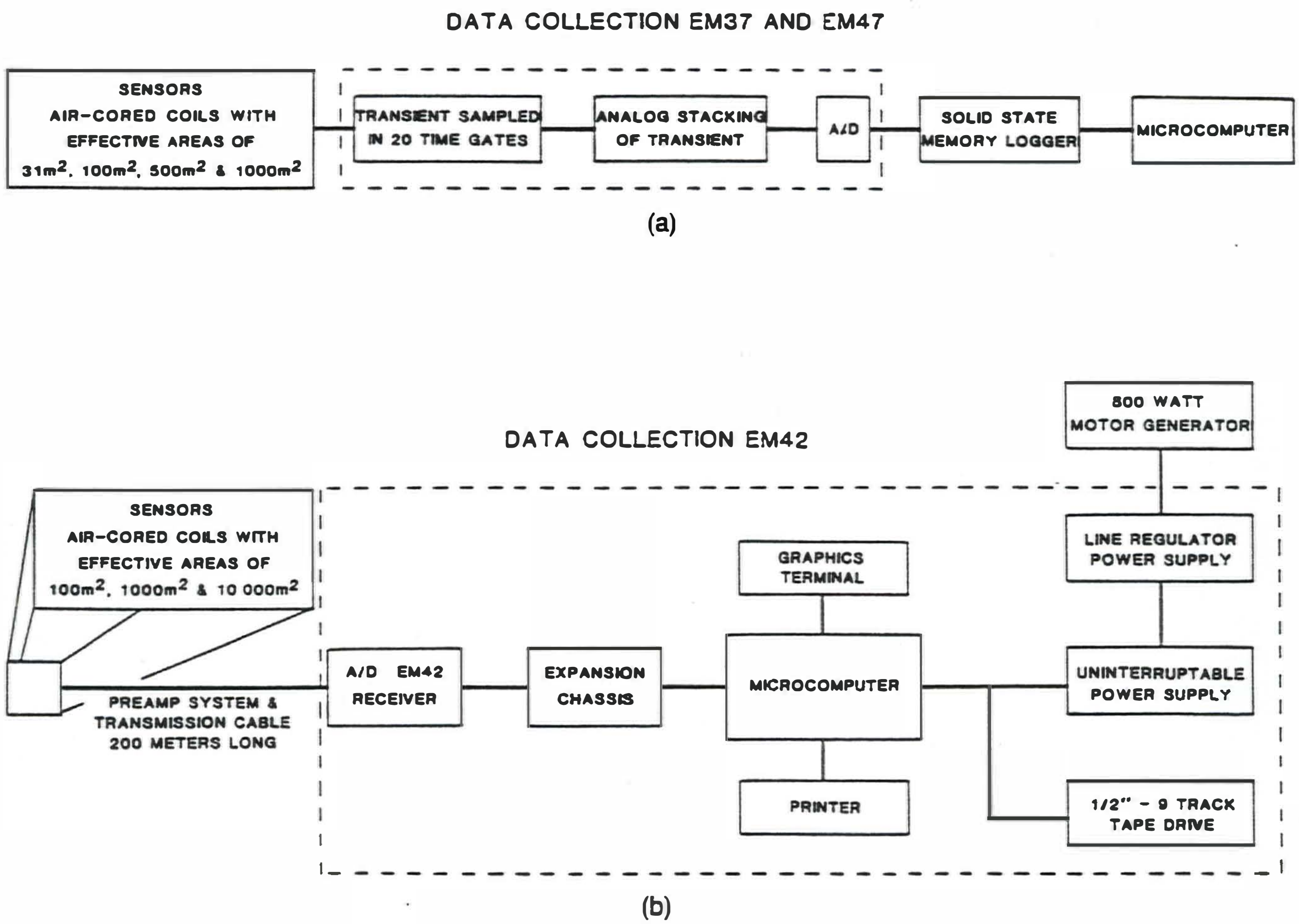

FIG. 5. Block diagrams of TDEM systems.

the EM-42 in typical ambient noise environments is 10^{-12} V/A-m^2

Data Acquisition

Recording transient decays with central loop soundings requires a large dynamic range, because emf$_z$ decays as $t^{-5/2}$, as shown in equation (1). This large dynamic range is often obtained by acquiring a data set in segments using different combinations of base frequencies, gains, and air coil receivers. An example of such a data set is given in Figure 6. The early time part of the curve was acquired at a base frequency of 3 Hz, 100 m^2 air coil and EM-37 receiver; the later time section was recorded with the EM-42 receiver, a 10 000 m^2 air coil and a base frequency of 0.075 Hz. When the 10 000 m^2 coil is used, the early time segment of this curve is purposely saturated. It is common to collect data sets at two receiver polarities, various gain settings, base frequencies, and with receiver coils of different effective areas. These various data sets are combined in one transient-decay curve that is subsequently entered into inversion routines.

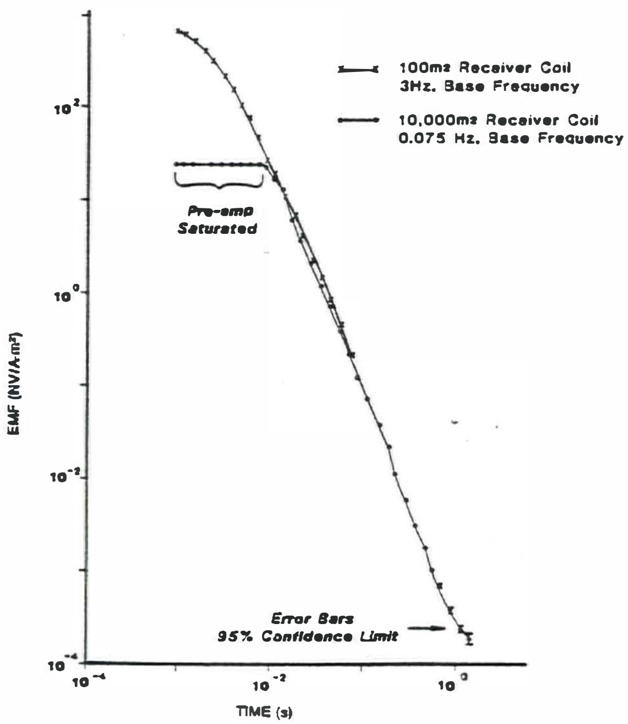

FIG. 6. Emf$_z$ measured in center of 500 m by 500 m transmitter loop.

Definition of Apparent Resistivity

All electrical and electromagnetic methods commonly transform the voltages or emf's measured into apparent resistivities. In TDEM several definitions of apparent resistivity are in use (Kaufman and Keller, 1983; Goldman, 1988) and the merits and pitfalls of the various definitions have been reviewed in Spies and Eggers (1986). These pitfalls are often avoided by (1) integrating inversions with available geologic data, and (2) using albums of forward-model curves for first-guess solutions. In all the case histories late-stage (Kaufman and Keller, 1983) apparent resistivity curves are used. Two reasons for that selection were (1) over a large range of time late-stage behavior is observed in central-loop soundings, and (2) extensive volumes of late-stage model curves (Goldman and Rabinovich, 1974) are available.

Data Interpretation

All the examples shown in the case histories were interpreted by one-dimensional (1-D) inversions of the data using a ridge-regression inversion program (ARRTI, Interpex Ltd, 1985). The input for the program are the emfs measured in various time gates, certain equipment and survey parameters (transmitter loop size, current, ramp time, receiver coil effective area), and number of layers to be used in the inversion. Also, an initial solution is entered. Goldman (1988) discussed the dependence of inversion routines on this first guess. To mitigate convergence to unrealistic solutions, first guesses are made to correspond with known geologic conditions, and depending on the quality of available geologic information, certain parameters in a geoelectric section may be fixed at specific values, e.g., as observed in borehole logs.

In TDEM soundings there is merit in carefully considering inversion errors at each time gate, because each section of the curve is often diagnostic of a certain depth section (Kaufman and Keller, 1983; Raiche and Gallagher, 1985). This can be illustrated by a central loop TDEM sounding with a 500 m by 500 m transmitter loop over a Tertiary valley fill in Nevada. Figure 7b shows the late-stage, apparent resistivity curve and Figure 7a two 1-D inversions for this sounding. The difference between the two inversions is the absence of a resistive layer (basalt flow) in section 1, and its presence in section 2. Figure 7c shows the error between the measured data and the two inversions. The increased error over the early time range suggested inserting an additional layer into the inversion. The existence of this resistive layer has been confirmed by drilling.

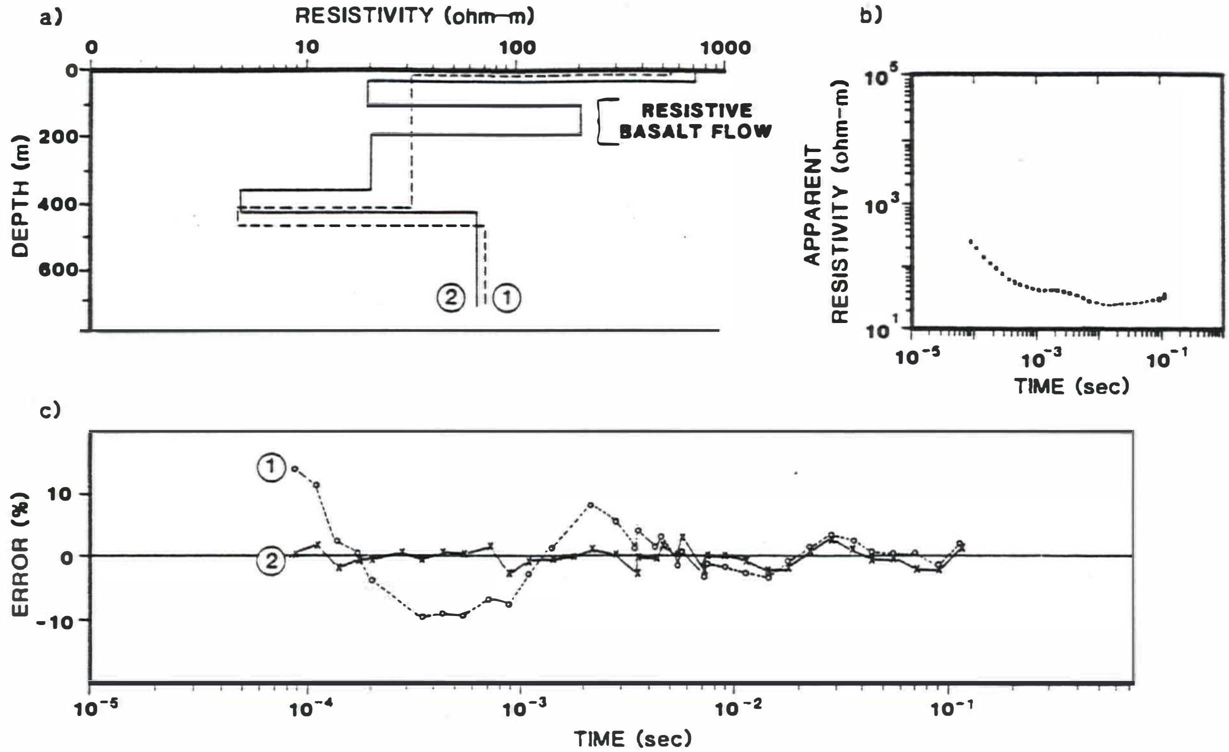

FIG. 7. Geoelectric sections (a) derived from 1-D inversions of measured apparent resistivity curve (b) over Tertiary Valley fill in Nevada. For each geoelectric section error of inversion is shown as function of time (c).

Validity of One-Dimensional Interpretation

The complexity of evaluating the influence of 2-D and 3-D structures of TDEM data is often cited as a disadvantage (Goldman, 1988). Indeed, currently, computations of 2-D and 3-D structures require computations that cannot be economically and practically applied in routine exploration programs. From the 2-D and 3-D computations (Newman et al., 1987) that have been published, important conclusions can be derived about the validity of 1-D interpretations in the presence of 2-D and 3-D structures. For example, Newman et al. (1987) computed the response over a resistive and conductive 3-D structure buried in a layered half-space at a depth of about 300 m. They reached the conclusion that 1-D inversions gave good estimates of the depth of burial of the 3-D structure, but unreliable depth extent and resistivities of the 3-D body. They used relatively large transmitter loops (1000 m by 1000 m) compared to exploration depth (1000 m) in their computations.

Drill-hole control is seldom sufficient to evaluate thoroughly the influence of 2-D and 3-D structures on a data set. Our experience, based on several thousand soundings with transmitter loop dimensions varying from 30 m by 30 m to 500 m by 500 m, is that 1-D interpretations yield good depth interpretations in the vast majority of work undertaken. Nevertheless, practical algorithms for data interpretation in the presence of 2-D and 3-D structures is an important need in TDEM soundings. Some efforts in that direction are promising (James, 1988).

Case Histories

Case History—High Level Nuclear Waste Repository Siting

The storage panels of the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico are being mined in the bedded salts of the Salado formation at a depth of about 600 m below ground surface. Underlying the Salado formation is the Castile formation, which is composed primarily of anhydrite and halite. It is known from oil and gas drilling that the Bell Canyon formation, underlying the Castile formation, can contain brines (Barrows et al., 1982).

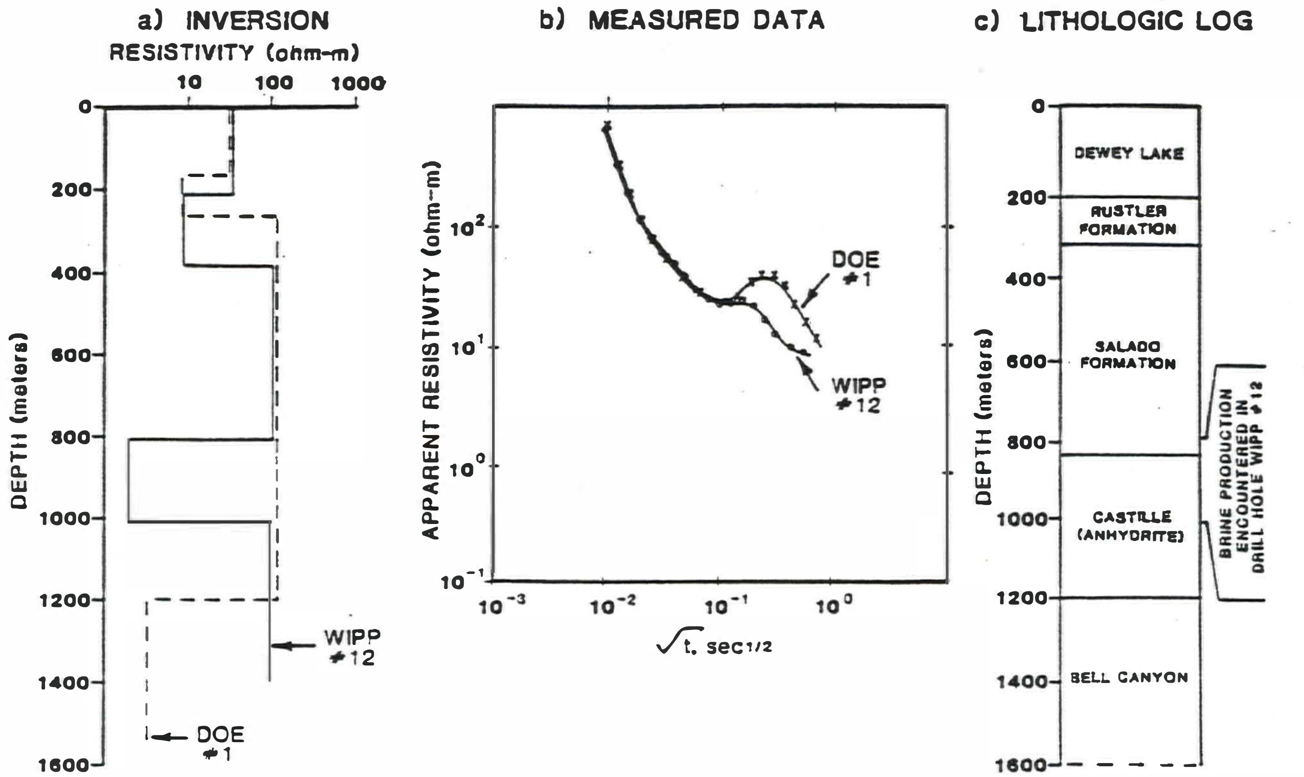

FIG. 8. Two measured late-stage apparent resistivity curves (b) and corresponding geoelectric sections derived from 1-D inversions (a). Also shown is a lithologic log common to both sounding locations (c).

The concept for placing a high level nuclear waste (HLW) repository in bedded salts at 600 m is to exploit the low hydraulic permeabilities of overlying bedded salts, and underlying anhydrites and halites. However, in the general vicinity of Carlsbad, New Mexico, drill holes encountered pressurized brine reservoirs at depths between 730 m and 915 m in the Castille formation (Register, 1981). The objective of TDEM surveys was to map the depth of first occurrence of brine over the waste storage panels and surrounding area.

A TDEM survey was conducted on a 500 m grid using central loop TDEM soundings over the waste storage panels and at selected drill hole locations. The transmitter loop dimensions employed were 500 m by 500 m and the TDEM equipment used was the Geonics EM-42.

Figure 8b shows two apparent resistivity curves located within 150 m of two drill hole locations, WIPP #12 and DOE #1. The resistivity layering derived from 1-D inversions for these two soundings is given in Figure 8a., and Figure 8c shows a lithologic log common to WIPP #12 and DOE #1. In the drilling of WIPP #12, brines were encountered at a depth of 850 m, and in drill hole DOE #1 no brines were encountered to total depth (TD = 900 m). The depth of first occurrence of brine observed in WIPP #12 is in excellent agreement with the depth of the low resistivity layer derived from the 1-D inversion of the adjacent TDEM sounding. Depth of occurrence of the low resistivity layer derived from the TDEM inversion near drill hole DOE #1 is at 1200 m, some 300 m below TD, and at a depth corresponding to the Bell Canyon formation.

The 1-D inversions of TDEM soundings over the waste storage panels showed first depth of occurrence of brine below 1050 m. This depth generally corresponds to the Bell Canyon formation. Thus, the 1-D interpretations of the depth of first occurrence of brine were consistent with available ground truth. A major concern remains the minimum dimensions of brine occurrences detectable with central loop soundings. This problem is being addressed by 2-D and 3-D forward modeling.

There are several other important objectives in environmental geophysics for mapping depth of first occurrences of brine, such as:

(1) Siting injection zones for oil field brines, and other liquid waste injection wells. Regulations require

injection zones to have a concentration of dissolved solids greater than 10 000 ppm and confining zones must separate US drinking water supplies (USDW) and injection zones (Federal Register, 1987).

(2) Monitoring migration of wastes upward from injection zones along fractures, abandoned wells, or faulty casings (Fitterman et al., 1986).

Mapping Encroachment of Salt Water Into Fresh-Water Aquifers

Intrusion of salt water in coastal aquifers often has as its main cause excessive withdrawal of ground water. It has long been recognized that surface electrical or electromagnetic methods can be effective in mapping fresh water—salt water interfaces (Flathe, 1964). Here, the application of TDEM surveys for this purpose is illustrated by a case history from the Salinas Valley, CA (Mills et al., 1988). A schematic hydrogeologic cross-section of the study area is given in Figure 9. There are four aquifer zones (1) a perched aquifer in which the ground water is heavily contaminated by fertilization, (2) a 180 ft aquifer approximately 60 m thick in which salt water has intruded under about 15 000 acres, (3) a 400 ft aquifer in which salt-water intrusion has been observed under about 6600 acres, and (4) a 900 ft aquifer in which no salt-water intrusion has yet been observed.

Thus, salt-water intrusion has progressed farthest inland into the 180 ft aquifer, so that to map water quality in the 400 ft aquifer requires exploration through a 180 ft aquifer containing high concentrations of dissolved solids. This information was used in designing the survey. To map salt-water encroachment in the 180 ft aquifer 100 m by 100 m transmitting loops were em-

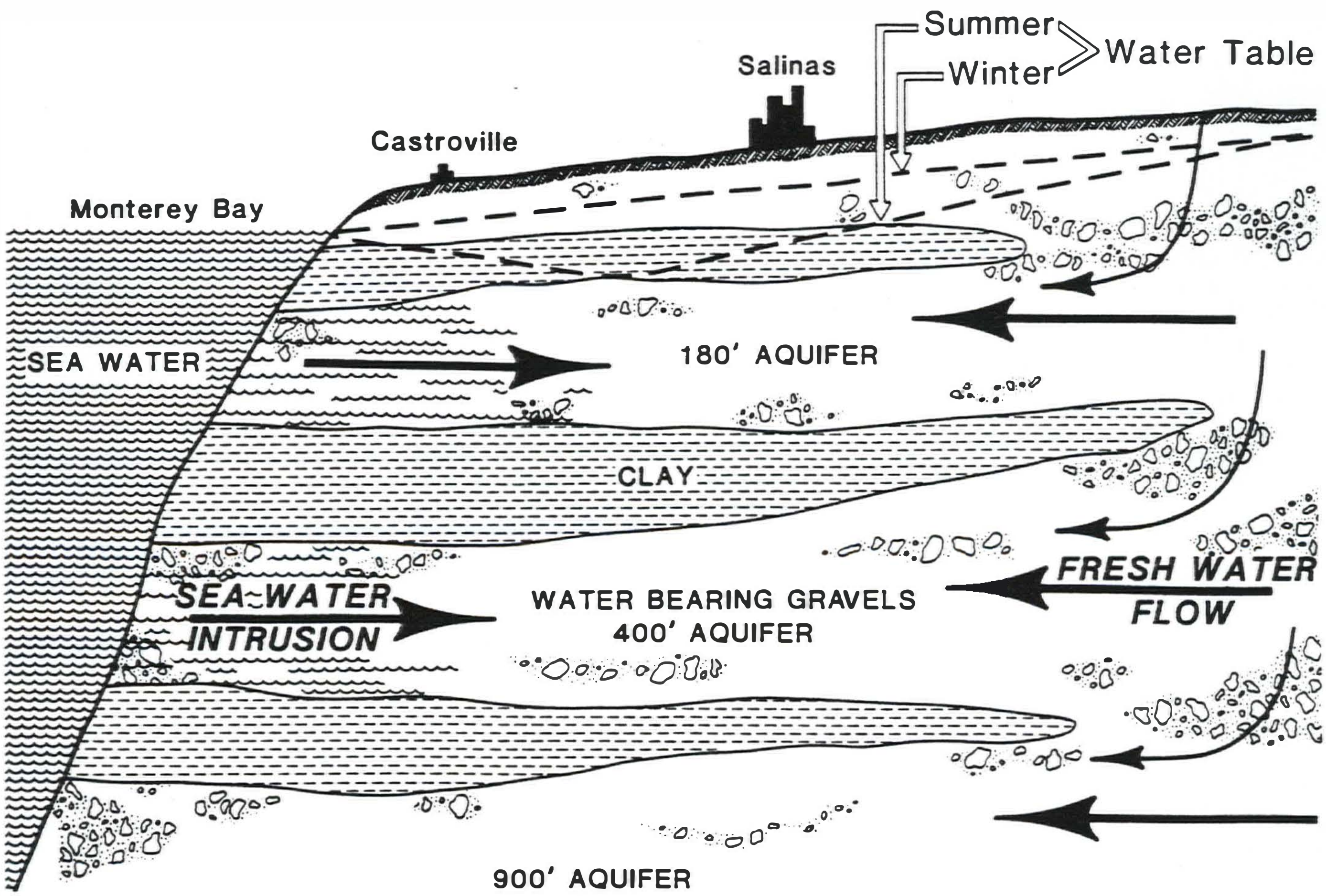

FIG. 9. Schematic hydrogeologic section of study area in the Salinas Valley, CA.

ployed. These transmitting loop dimensions provided sufficient field strength to derive the resistivity variation in the 180 ft aquifer. Larger transmitting loop dimensions (200 m by 200 m) were employed for exploration in the 400 ft aquifer. Approximately 100 stations were measured.

A series of four late-stage apparent-resistivity curves along cross-section B-B′ (Figure 12) are shown on Figure 10 along with geoelectric sections derived from 1-D inversions. Figure 11 shows the geoelectric section derived from TDEM soundings along profile B-B′. In the 180 ft aquifer the resistivity gradually increases inland from 1.5 Ω · m (station L24/3) to 18 Ω · m (station L10/1). In the 400-ft aquifer the resistivity increased from 6.0 Ω · m to in excess of 20 Ω · m.

Information from monitoring wells maintained by the Monterey County Flood Control and Water Conservation District was used to help constrain the number of layers used for the inversions of the TDEM data, and to correlate formation resistivities with equivalent chloride concentration. Correlation of formation resistivities with chloride concentration showed that a resistivity of approximately 8 Ω · m corresponds to a 500 ppm chloride concentration. Figure 12 shows the surface projection of the 500 ppm isochlor contours (8 Ω · m formation resistivity) in the 180 ft and 400 ft aquifers. The 500 ppm isochlor, based on monitoring wells, is also shown. There is more detail in the contours derived from the TDEM surveys mainly because of the higher station density.

These types of TDEM surveys have now been performed in several areas of Florida (Steward and Gay, 1981), Massachusetts (Fitterman and Hoekstra, 1982), California (Mills et al., 1988), and New York. Important advantages of TDEM soundings in these surveys are:

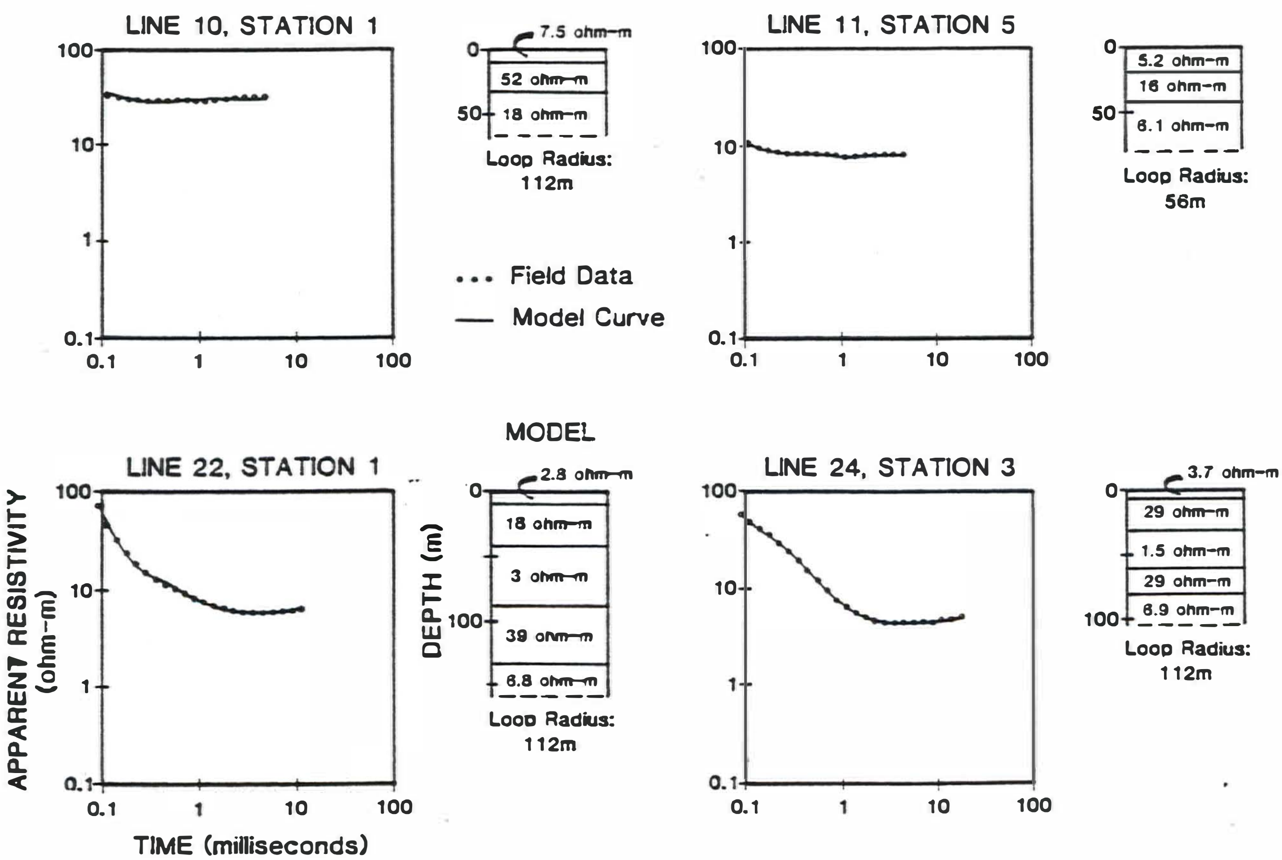

FIG. 10. Four apparent resistivity curves and inverted geoelectric sections along section B-B′ (Figure 12).

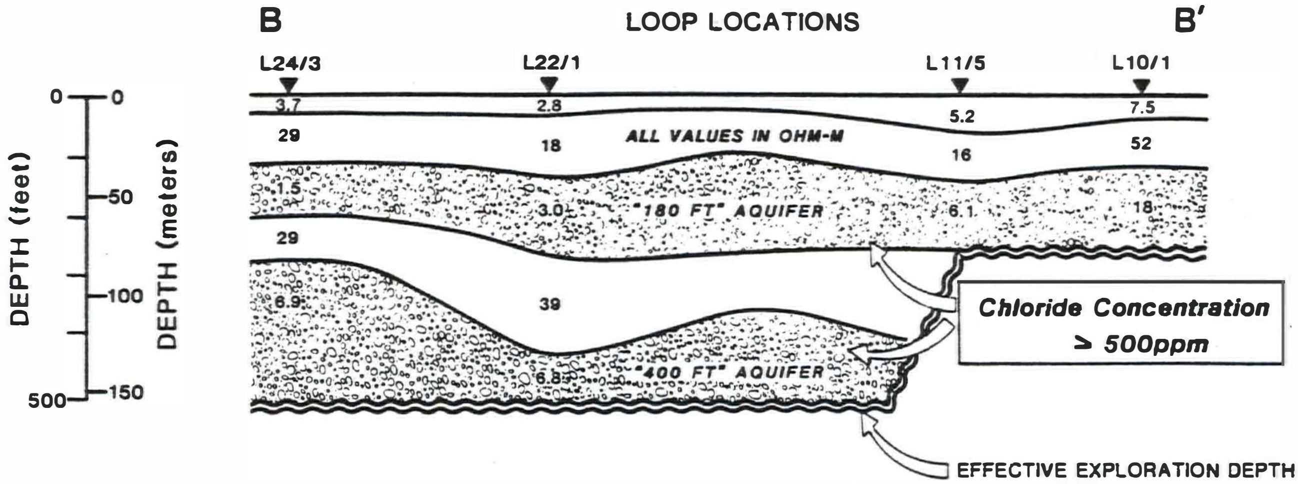

FIG. 11. Geoelectric section B-B′ derived from TDEM soundings.

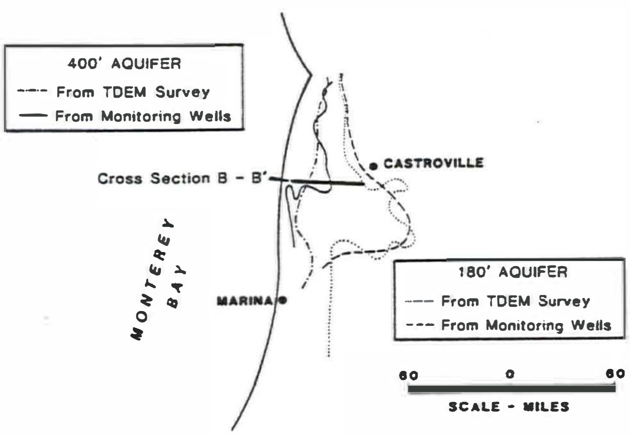

FIG. 12. Comparison of position of 500 ppm isochlor in 180 ft and 400 ft aquifers derived from monitoring wells and TDEM soundings.

(1) Coastal areas are often urbanized and limited space is available for measurements. TDEM measurements were often made in available open spaces such as high school athletic fields and parks.
(2) Ambient electrical noise (e.g., powerlines and radio stations) is high in developed areas. The signal stacking used in TDEM has proven an effective way for recovering signal from noise.

The utility of TDEM surveys for water management plans are in (1) providing optimum location for placement of monitoring and production wells, (2) determining depth of completion of such wells, (3) interpolating the position of the fresh water–saline water interface between wells, and (4) monitoring the movement of the interface over time. Geophysical stations can be moved from year to year, while monitoring wells lose some of their usefulness once the fresh water–saline water interface has migrated past their locations.

Shallow TDEM Surveys

Important exploration objectives for shallow (< 50 m) electrical exploration in environmental geophysics are

- mapping continuity of confining layers, such as clay lenses;
- mapping the presence of contaminants (e.g., originating from brine ponds) and pathways for migration of contaminants, such as fractures and shear zones;
- correlating hydraulic transmissivities to electrical conductance (e.g., Huntley, 1986).

The geophysical methodologies applied to these exploration problems have mainly been dc resistivity soundings (e.g., Evans et al., 1982) and frequency-domain electromagnetic conductivity profiling (e.g., McNeill, 1982). With the recent availability of a TDEM system (Geonics EM-47) for shallow exploration, some of these objectives are now within the exploration depth range of TDEM. An example of shallow central-loop soundings with a prototype EM-47 is a survey over relatively thin basalt flows near Golden, Colorado.

On North and South Table Mountain in Golden, Colorado, lava flows overlie the Denver formation. Figure 13a shows the geologic section of the upper 100 m on North Table Mountain (Waldschmidt, 1939). Figure 13c shows an apparent resistivity curve measured in the center of a 30 m by 30 m transmitter loop with the EM-47 and its 1-D inversion. A peak current of 2 A was driven through the loop, and the ramp turn-off (Figure 4a) was 2.5 μs. The first time gate was centered at 6.4 μs and data were collected at base frequencies of 300 Hz and 30 Hz. The geoelectric section derived from the 1-D inversion (Figure 13b) shows good agreement between geologic boundaries and breaks in resistivity.

For this geoelectric section and for 30 m by 30 m transmitter loops (R = 15 m), late stage commences at about 10^{-5} s (Figure 3), so that almost the entire measured curve is in late-stage. Also shown on Figure 13c are forward modeled curves with different thicknesses of the upper basalt flow, while all other parameters were held constant. Large changes in the curves occur mainly

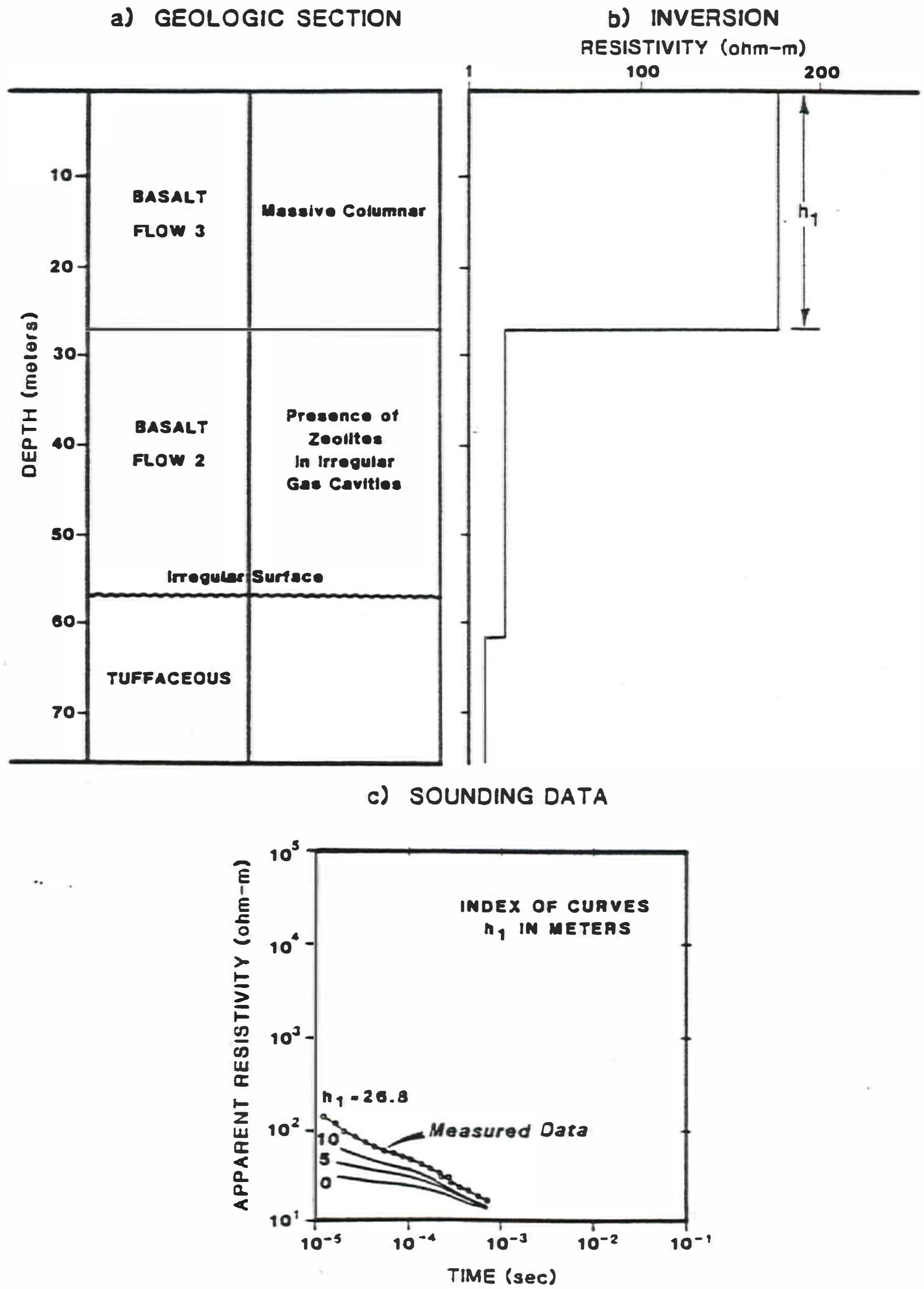

FIG. 13. (a) Geologic section of North Table Mountain, Golden, CO; (b); and geoelectric section derived from 1-D inversion of central loop sounding data with 30 m by 30 m transmitter loop; (c) the measured apparent resistivities are superimposed on a series of forward model curves in which the thickness of the upper basalt layer is varied.

over the time range from 10^{-5} s to 10^{-3} s; the time range covered by EM-47 measurements.

The conclusions from a number of conducted surveys is that the EM-47 can be employed in the depth range from 5 m to 75 m, depending somewhat on the geoelectric section. Since transmitter loop dimensions of 30 m by 30 m can be employed, survey productivity is high (30 to 50 stations per day). The TDEM EM-47 promises to be an effective methodology for electrical mapping in environmental geophysics, particularly in urban areas where space is limited and ambient noise is high.

Discussion

Focusing on the use of TDEM methods in environmental geophysics is such a narrow focus that there is a danger of overstating the utility of TDEM, compared to other electrical and electromagnetic measurement techniques. Raiche et al. (1985) and Fitterman et al. (1988) show that the range of equivalence in some geoelectric sections can in principle be reduced by combined use of dc resistivity and TDEM soundings. It is, therefore, important to note that the exploration objective in all three case histories consisted of determining depth to a conductive stratum, objectives optimally suited for electromagnetic techniques. TDEM surveys and other electromagnetic techniques have limitations for detecting thin resistive strata, and such limitations are readily evaluated by forward modeling.

One advantage of TDEM not evident from forward modeling computations is the absence of scatter in the data. The data scatter frequently observed in dc resistivity soundings, and distant source techniques (controlled source audiomagnetotelluric, audiomagnetotelluric, and magnetotelluric methods) are often due to lateral variation in resistivity and measurement of the electric field. The scatter is reduced in central loop TDEM soundings mainly because of the short source/receiver separation and measurement of the time derivative of magnetic fields. The apparent resistivity curves shown in these investigations are typical of a large number of stations. No smoothing of the data is performed before inversions.

The recent availability of a shallow TDEM system for the exploration depth range from 5 m to 75 m makes this technique suitable for such environmental studies as well-site protection programs, and mapping plumes of ground-water contamination. Contamination plumes are often confined to narrow zones, and the high lateral resolution possible with shallow central loop TDEM soundings allows definition of both the lateral and vertical extent of such plumes.

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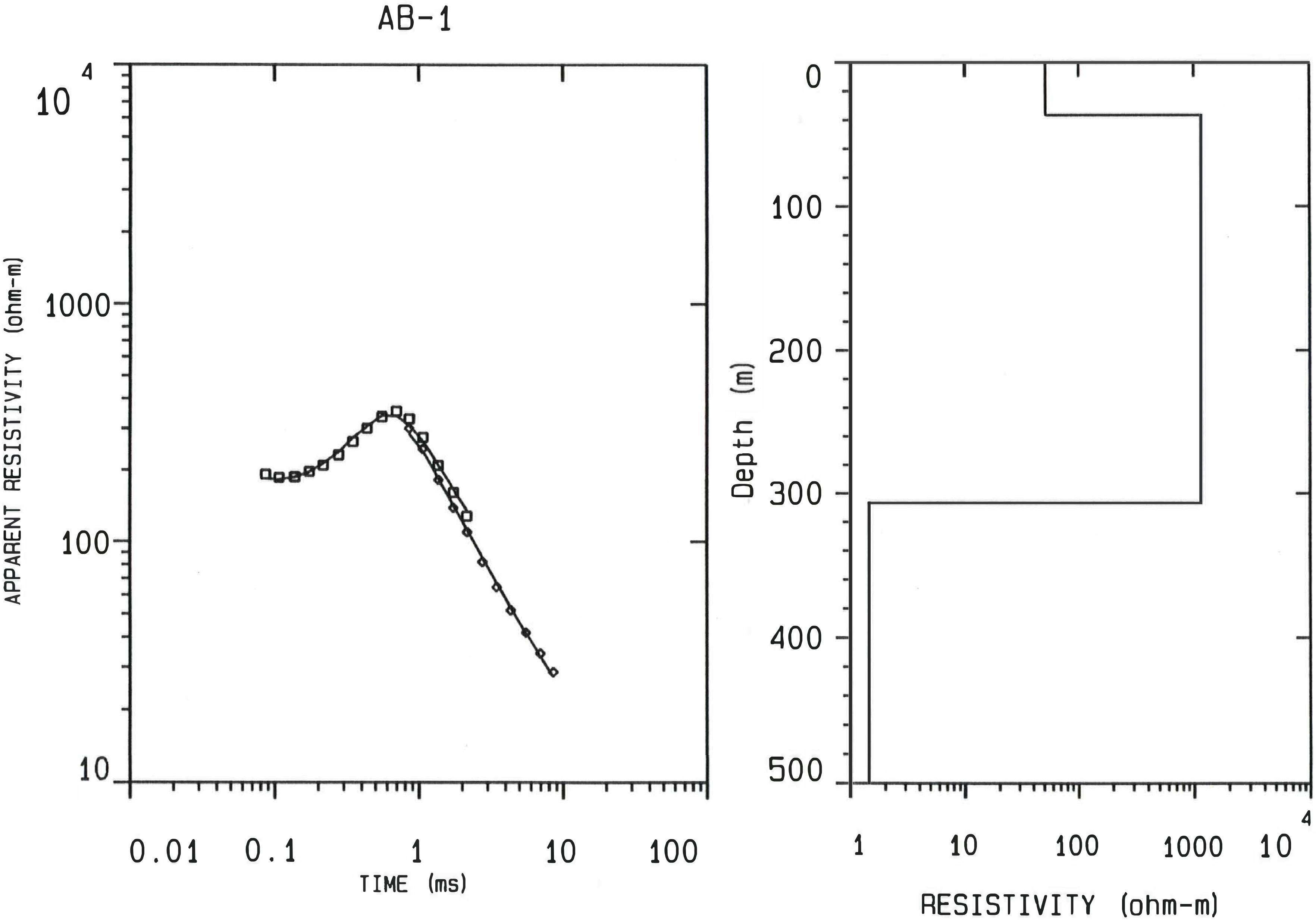


AB-1
APPARENT RESISTIVITY (ohm-m)
10 4
1000
100
10
0.01
0.1
1
10
100
TIME (ms)
Depth (m)
0
100
200
300
400
500
1
10
100
1000
10 4
RESISTIVITY (ohm-m)

DATA SET: AB-1

CLIENT: A&B PROPERTIES, INC
LOCATION: KAILUA, MAUI
COUNTY: MAUI
PROJECT: KAILUA WATER WELLS
LOOP SIZE: 152.000 m by 152.000 m
COIL LOC: 0.000 m (X), 0.000 m (Y)
SOUNDING COORDINATES: E: 1.0000 N: 1.0000

DATE: 05-10-98
SOUNDING: 1
ELEVATION: 256.00 m
EQUIPMENT: Geonics PROTEM
AZIMUTH:
TIME CONSTANT: NONE
SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 4.912 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			256.0	840	
1	51.09	36.52	219.4	720	0.714
2	1151.0	270.0	-50.60	-166	0.234
3	1.44				

ALL PARAMETERS ARE FREE

CURRENT: 19.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 7 RAMP TIME: 110.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	37351.7	39939.4	-6.92
2	0.108	22679.8	23345.8	-2.93
3	0.138	12174.2	12185.7	-0.0949
4	0.175	6205.1	6217.8	-0.205
5	0.218	3268.7	3188.6	2.45
6	0.278	1535.6	1473.1	4.06
7	0.351	704.9	664.8	5.67
8	0.438	332.6	324.9	2.32
9	0.558	153.7	150.7	1.94
10	0.702	80.01	85.89	-7.35
11	0.858	53.94	59.55	-10.39
12	1.06	41.15	43.15	-4.87
13	1.37	33.10	33.07	0.108
14	1.74	27.07	25.82	4.61

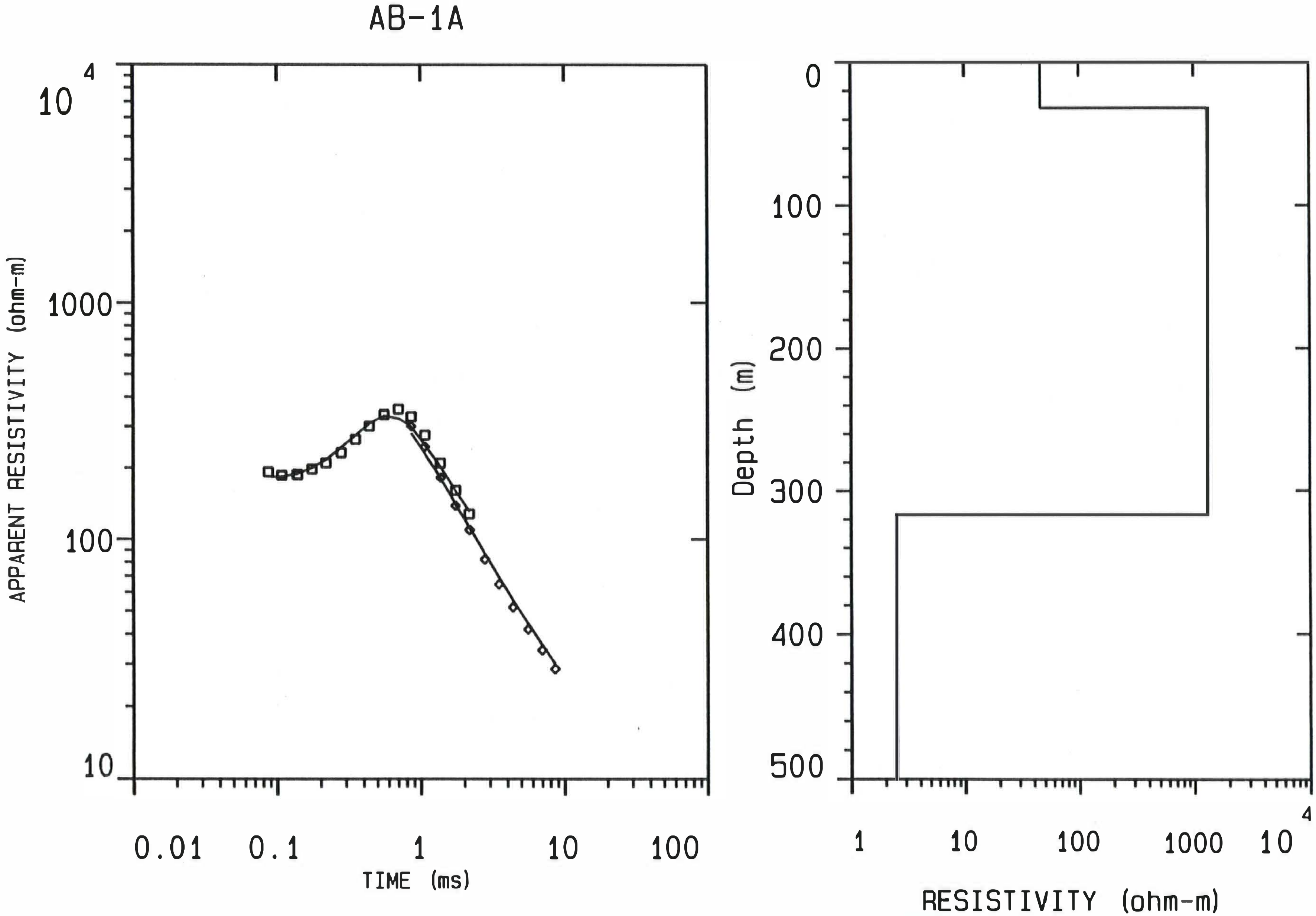
No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	2.17	22.03	20.38	7.51

CURRENT: 19.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 110.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
16	0.857	62.34	67.35	-8.04
17	1.06	48.92	50.63	-3.50
18	1.37	40.89	40.28	1.50
19	1.74	33.88	32.73	3.40
20	2.17	27.77	26.96	2.92
21	2.77	23.16	21.87	5.56
22	3.50	18.59	17.63	5.18
23	4.37	14.84	14.33	3.46
24	5.56	11.20	11.27	-0.605
25	6.98	8.54	8.91	-4.28
26	8.56	6.69	7.11	-6.27

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.88				
P 2	-0.01	0.06			
P 3	0.05	-0.06	0.56		
T 1	-0.14	-0.08	0.08	0.82	
T 2	0.02	0.01	-0.04	0.03	0.99
	P 1	P 2	P 3	T 1	T 2


AB-1A
APPARENT RESISTIVITY (ohm-m)
10^4
1000
100
10
0.01
0.1
1
10
100
TIME (ms)
Depth (m)
0
100
200
300
400
500
1
10
100
1000
10^4
RESISTIVITY (ohm-m)

DATA SET: AB-1A

CLIENT:	A&B PROPERTIES, INC	DATE:	05-10-98
LOCATION:	KAILUA, MAUI	SOUNDING:	1
COUNTY:	MAUI	ELEVATION:	256.00 m
PROJECT:	KAILUA WATER WELLS	EQUIPMENT:	Geonics PROTEM

LOOP SIZE: 152.000 m by 152.000 m AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y) TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 1.0000 N: 1.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 7.992 PERCENT

L #	RESISTIVITY (ohm-m)		THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
				256.0	840	
1	46.11		31.90	224.0	735	0.691
2	1319.7		284.8	-60.76	-199	0.215
3	2.50	*				

"*" INDICATES FIXED PARAMETER

CURRENT:	19.00 AMPS	EM-37	COIL AREA:	100.00 sq m.
FREQUENCY:	30.00 Hz	GAIN: 7	RAMP TIME:	110.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	37351.7	40068.0	-7.27
2	0.108	22679.8	23147.3	-2.06
3	0.138	12174.2	12016.5	1.29
4	0.175	6205.1	6074.3	2.10
5	0.218	3268.7	3121.2	4.51
6	0.278	1535.6	1419.9	7.53
7	0.351	704.9	665.2	5.62
8	0.438	332.6	321.4	3.37
9	0.558	153.7	155.8	-1.37
10	0.702	80.01	91.97	-14.93
11	0.858	53.94	62.42	-15.70
12	1.06	41.15	47.53	-15.50
13	1.37	33.10	35.15	-6.18
14	1.74	27.07	27.33	-0.965

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	2.17	22.03	21.33	3.19

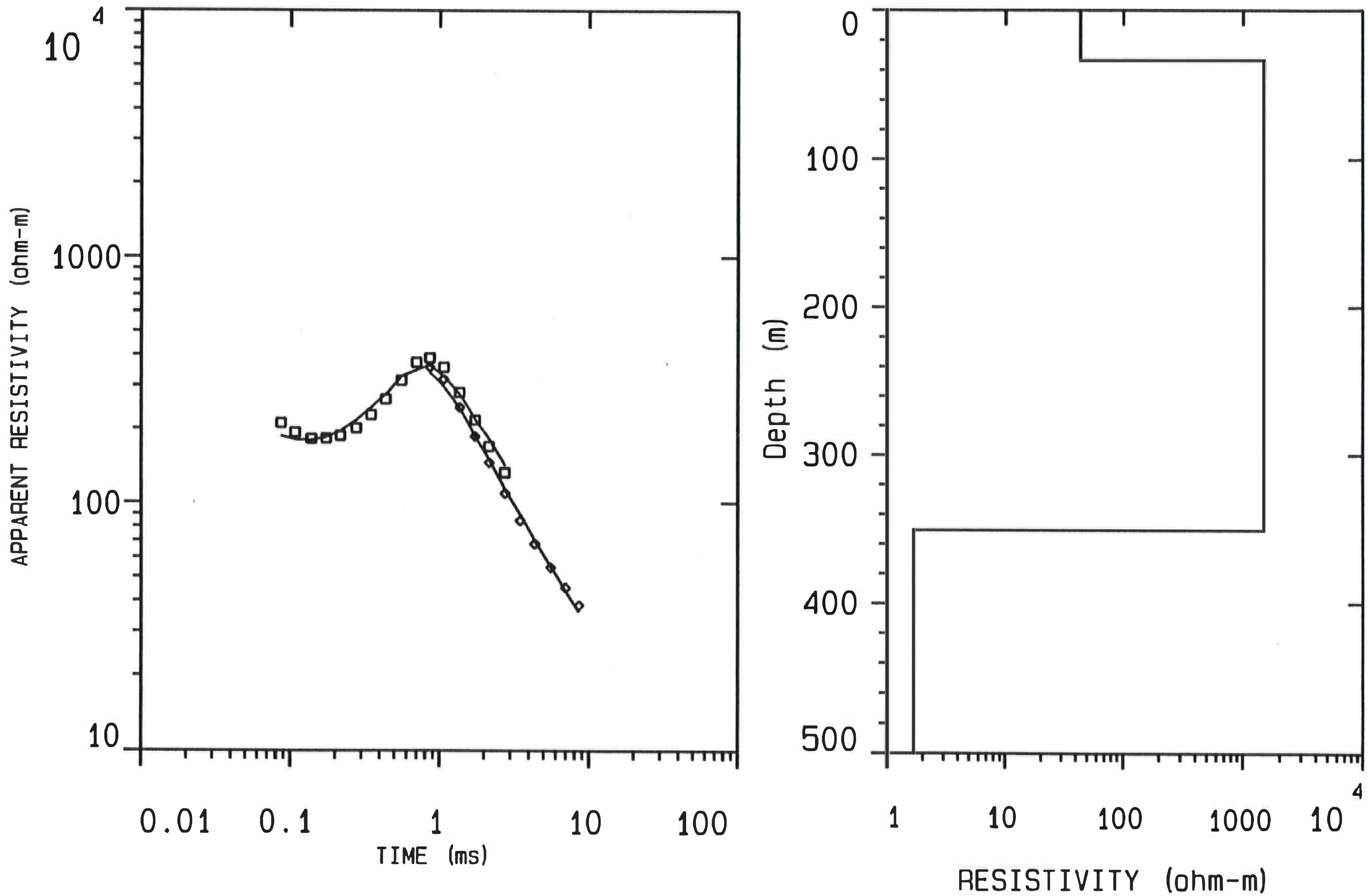
CURRENT: 19.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 110.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
16	0.857	62.34	69.14	-10.91
17	1.06	48.92	53.96	-10.30
18	1.37	40.89	41.33	-1.06
19	1.74	33.88	33.22	1.96
20	2.17	27.77	26.90	3.13
21	2.77	23.16	21.34	7.86
22	3.50	18.59	16.85	9.32
23	4.37	14.84	13.39	9.77
24	5.56	11.20	10.28	8.20
25	6.98	8.54	7.90	7.46
26	8.56	6.69	6.18	7.72

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.91				
P 2	-0.01	0.06			
F 3	0.00	0.00	0.00		
T 1	-0.10	-0.08	0.00	0.88	
T 2	0.01	0.01	0.00	0.01	1.00
	P 1	P 2	F 3	T 1	T 2

AB-2



10^4
1000
100
10
APPARENT RESISTIVITY (ohm-m)
0.01
0.1
1
10
100
TIME (ms)
0
100
200
300
400
500
Depth (m)
1
10
100
1000
10^4
RESISTIVITY (ohm-m)

DATA SET: AB-2

CLIENT:	A&B PROPERTIES, INC	DATE:	05-12-98
LOCATION:	KAILUA, MAUI	SOUNDING:	2
COUNTY:	MAUI	ELEVATION:	296.00 m
PROJECT:	KAILUA WATER WELLS	EQUIPMENT:	Geonics PROTEM

LOOP SIZE: 213.000 m by 213.000 m AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y) TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 200.0000 N: -2.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 8.421 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			296.0	970	
1	43.44	33.33	262.6	861	0.767
2	1491.1	317.3	-54.73	-180	0.212
3	1.69				

ALL PARAMETERS ARE FREE

CURRENT: 14.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	47318.0	56472.1	-19.34
2	0.108	31090.9	34421.8	-10.71
3	0.138	18389.9	18807.8	-2.27
4	0.175	10123.3	9918.5	2.02
5	0.218	5625.4	5256.7	6.55
6	0.278	2742.9	2468.2	10.01
7	0.351	1274.7	1142.2	10.39
8	0.438	585.8	547.9	6.45
9	0.558	246.4	230.3	6.53
10	0.702	107.4	118.7	-10.57
11	0.858	60.72	67.52	-11.20
12	1.06	40.40	45.68	-13.07
13	1.37	30.71	31.54	-2.68
14	1.74	24.98	24.66	1.26

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	2.17	20.83	18.79	9.77
16	2.77	16.42	14.85	9.57

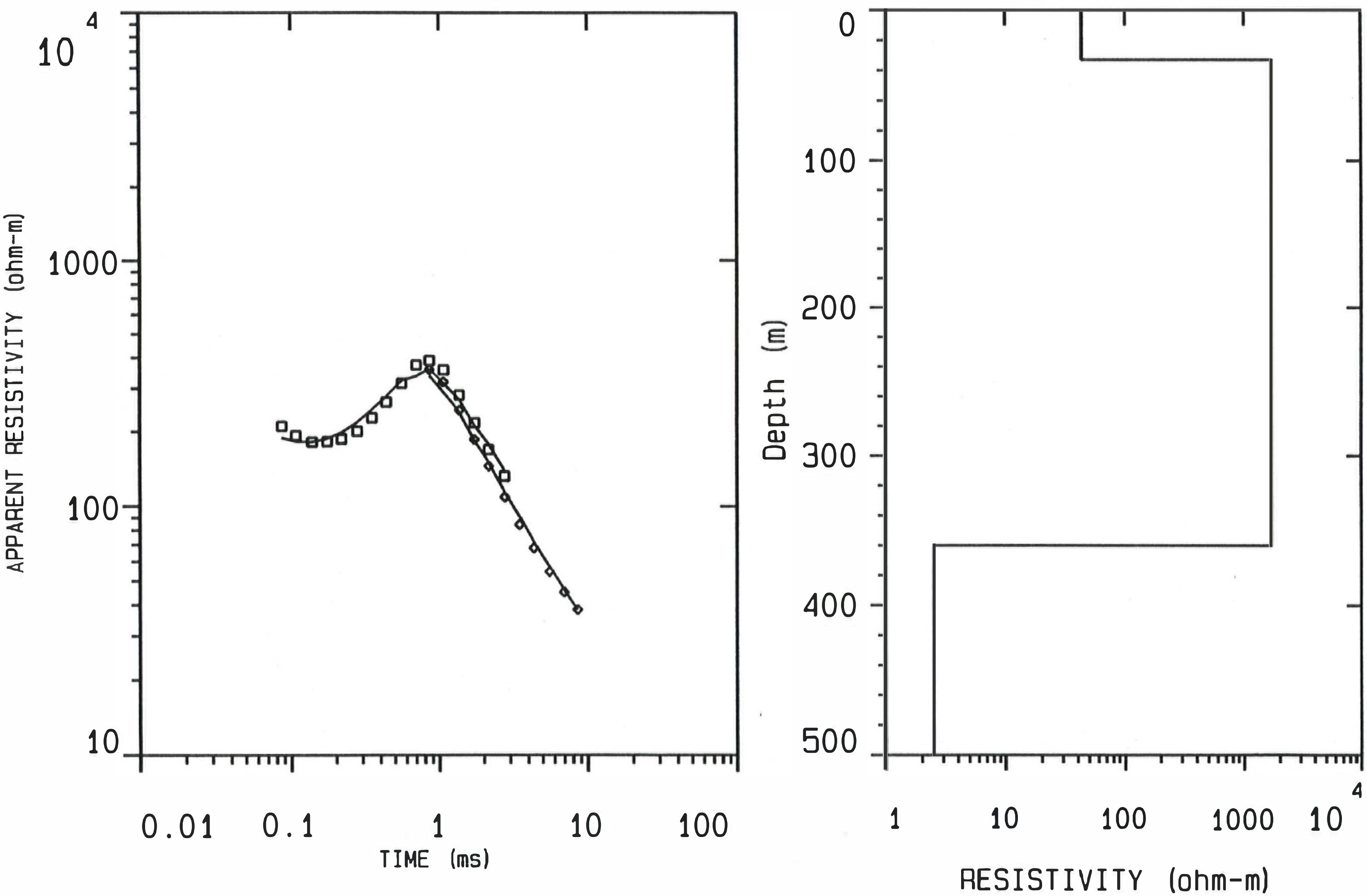
CURRENT: 14.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
17	0.857	69.50	75.10	-8.05
18	1.06	47.94	52.89	-10.31
19	1.37	37.90	38.49	-1.56
20	1.74	31.41	31.33	0.257
21	2.17	26.24	25.16	4.11
22	2.77	21.96	20.82	5.20
23	3.50	17.91	16.54	7.65
24	4.37	14.28	13.63	4.55
25	5.56	10.87	10.71	1.42
26	6.98	8.17	8.53	-4.47
27	8.56	6.25	6.83	-9.32

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.93				
P 2	0.01	0.06			
P 3	0.03	-0.07	0.52		
T 1	-0.08	-0.04	0.05	0.91	
T 2	0.01	0.00	-0.04	0.01	0.99
	P 1	P 2	P 3	T 1	T 2

AB-2A



10^4
1000
100
10
APPARENT RESISTIVITY (ohm-m)
0.01
0.1
1
10
100
TIME (ms)
0
100
200
300
400
500
Depth (m)
1
10
100
1000
10^4
RESISTIVITY (ohm-m)

DATA SET: AB-2A

CLIENT: A&B PROPERTIES, INC
LOCATION: KAILUA, MAUI
COUNTY: MAUI
PROJECT: KAILUA WATER WELLS
LOOP SIZE: 213.000 m by 213.000 m
COIL LOC: 0.000 m (X), 0.000 m (Y)
SOUNDING COORDINATES: E: 200.0000 N: -2.0000

DATE: 05-12-98
SOUNDING: 2
ELEVATION: 296.00 m
EQUIPMENT: Geonics PROTEM
AZIMUTH:
TIME CONSTANT: NONE
SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 9.667 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			296.0	970	
1	43.43	33.05	262.9	863	0.760
2	1701.8	326.9	-64.04	-210	0.192
3	2.50 *				

"*" INDICATES FIXED PARAMETER

CURRENT: 14.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0867	47318.0	55574.7	-17.44
2	0.108	31090.9	33797.2	-8.70
3	0.138	18389.9	18428.6	-0.210
4	0.175	10123.3	9701.9	4.16
5	0.218	5625.4	5145.0	8.53
6	0.278	2742.9	2420.6	11.75
7	0.351	1274.7	1128.3	11.48
8	0.438	585.8	543.1	7.27
9	0.558	246.4	236.0	4.22
10	0.702	107.4	124.9	-16.34
11	0.858	60.72	68.96	-13.58
12	1.06	40.40	48.64	-20.39
13	1.37	30.71	32.90	-7.12
14	1.74	24.98	25.85	-3.51

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	2.17	20.83	19.40	6.85
16	2.77	16.42	15.29	6.89

CURRENT: 14.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
17	0.857	69.50	75.86	-9.15
18	1.06	47.94	55.18	-15.10
19	1.37	37.90	39.20	-3.44
20	1.74	31.41	31.88	-1.49
21	2.17	26.24	25.13	4.21
22	2.77	21.96	20.64	6.00
23	3.50	17.91	16.09	10.19
24	4.37	14.28	13.11	8.21
25	5.56	10.87	10.11	6.94
26	6.98	8.17	7.92	2.98
27	8.56	6.25	6.25	0.105

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.97				
P 2	0.02	0.07			
F 3	0.00	0.00	0.00		
T 1	-0.03	-0.03	0.00	0.96	
T 2	0.00	0.01	0.00	0.00	1.00
	P 1	P 2	F 3	T 1	T 2